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Sandia National Laboratories

Cavern leaching associated with 2017 oil sales and exchanges

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ABSTRACT

In 2017 small-scale drawdowns at the Strategic Petroleum Reserve (SPR) supported oil sales for the Bipartisan Budget Act of 2015 and the 21st Century Cures Act of 2015 as well as exchanges supporting relief efforts for hurricane Harvey. These drawdowns may affect cavern stability and available drawdowns, thus is important to assess the leaching effects on the cavern shape. Cavern shape estimates from the SANSMIC solution mining code suggest the shapes of 28 caverns were altered in 2017 to varying degrees depending on the total volume of water injected, the initial cavern shape and the distance between the hanging string depth and the oil-brine interface depth. A flaring of the cavern floor occurred in 13 caverns, a geomechanically unfavorable outcome that may require operational changes to preserve cavern integrity. Of the three caverns with post-sale sonars, SANSMIC predictions compared favorably to two but underpredicted the third.

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

Small water injections can have a major impact upon the available drawdowns of Strategic Petroleum Reserve (SPR) caverns and their stability (Eldredge et al., 2013). Some leaching effects may be documented using measurements of the oil brine interface depth and cavern geometry. However, these measurements can be expensive and may not be conducted following each sale. Alternatively, models may provide intermediate information on cavern conditions until post-sale measurements can be made. This report describes the use of the SANSMIC solution mining code to assess the magnitude of cavern leaching expected from the 2017 small-scale drawdowns at the SPR. The drawdowns supported oil sales for the Bipartisan Budget Act of 2015 and the 21st Century Cures Act of 2015 as well as exchanges supporting relief efforts for hurricane Harvey. These simulations used sonar-surveyed cavern shapes at the start of each leaching stage, actual hanging string depths, and the field reported flow quantities for water to estimate the new cavern shapes and leached volumes. Leaching due to the 2017 sales and exchanges altered the shapes of 28 caverns to varying degrees depending on the total volume of water injected, the initial cavern shape and the distance between the hanging string depth and the oil-brine interface depth. Total injected water volumes since the last sonar exceed 3 MMB for four caverns: BC18, BM103, BM111 and WH111. Sandia suggests sonar surveys for all four caverns since they exceed the 3-MMB water injection criteria for conducting a new sonar (Lord et al., 2011). A flaring of the cavern floor occurred in 13 caverns, with an extension of the toe to be the widest part of the cavern for 2 caverns: BM108 and WH011. As the flared floor is not geomechanically favorable (Eldredge et al., 2013), Sandia suggests considering alternative operations in those 13 caverns, such as moving the hanging string depth. Of the caverns with post-sale sonars, SANSMIC predictions compared favorably to BH104 and BM111 but underpredicted the maximum radial extent of leaching of WH011, possibly due to an averaging of the injection rate. Although SANSMIC is not validated for non-cylindrical caverns, it was able to predict the BC18 OBI within 2 ft of the post-sale measured value. The relative agreement in OBI depths suggests SANSMIC may capture first order leaching effects in these caverns. No caverns exceeded 15% increase in cavern volume, which would constitute an automatic expenditure of a drawdown for those caverns (Sobolik et al., 2018).

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
BC	Bayou Choctaw
BH	Big Hill
BM	Bryan Mound
OBI	Oil Brine Interface
Oil Brine Interface Rise	Height of the oil brine interface above the cavern floor
SANSMIC	Sandia Solution Mining Code
SPR	Strategic Petroleum Reserve
WH	West Hackberry

1. SUMMARY OF LEACHING IN 2017

Leaching due to the 2017 sales and exchanges altered the shapes of 28 caverns to varying degrees depending on the total volume of water injected, the initial cavern shape and the distance between the hanging string depth and the oil-brine interface depth. The effects of leaching were modeled using SANSMIC (Section 3). As discussed in Section 4, there were 2 caverns used at BC, 11 caverns at BH, 9 caverns at BM, and 6 caverns at WH. The distribution by site is shown in Figure 1-1. The results are discussed in Section 5 and summarized in Table 1-1.

Injection of 41.1 MMB of water created 6.7 MMB of cavern volume in 2017, or since the last sonar for the caverns with leaching in 2017.

Total injected water volumes exceeded 3 MMB since the last sonar for 4 caverns: BC18, BM103, BM111 and WH111. Sonars are suggested in these caverns as Sandia recommends sonar surveys after every 3 MMB of injected water (Lord et al., 2011). Four caverns had 2-3 MMB of water injected, 9 caverns had 1–2 MMB of water injected, and 11 caverns had 0–1 MMB of water injected (Figure 1-2).

The cavern volume created exceeded 0.6 MMB for 1 cavern: WH111. Six caverns had between 0.4 and 0.6 MMB of volume created, 7 caverns had 0.2 – 0.4 MMB of volume created and 14 caverns had 0 – 0.2 MMB of volume created as shown in Figure 1-3. No caverns exceeded the 15% increase in cavern volume, which would constitute an automatic expenditure of a drawdown for those caverns (Sobolik et al., 2018). The largest change in cavern volume occurred in WH111 with a 6.9% increase in cavern volume, halfway to an automatic expenditure of a drawdown in that cavern.

The 2017 leaching efficiency, defined as the ratio of the created cavern volume to the injected water volume, was 16 %, the slope of the best fit line (red line) in Figure 1-4. The norm of residuals for that fit was 0.03 indicating the linear fit was good and cavern volume grew linearly with injected water volume. The injected water volume was not correlated with the change in cavern radius (Figure 1-5).

A flaring of the cavern floor occurred in 13 of the caverns: BH104, BH106, BH107, BH108, BH109, BH114, BM103, BM108, BM111, BM115, WH011, WH103, WH113. The flaring resulted in an extension of the toe to be the widest part of the cavern for 2 caverns: BM108 and WH011.

SANSMIC predictions compared favorably to BH104 and BM111 but underpredicted the maximum extent of radial leaching of WH011 as discussed in Section 6. SANSMIC also predicted the BC18 OBI within 2 ft of the measured value.

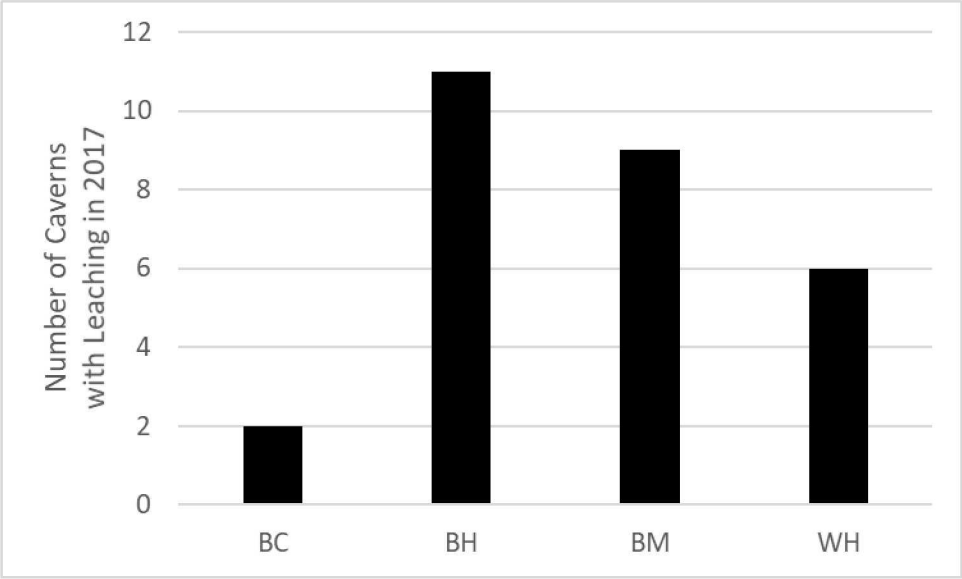

Figure 1-1 Distribution by site of caverns with leaching in 2017.

Table 1-1 Summary of leaching simulations for 2017.

Cavern	Latest sonar	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Initial Cavern Volume (MMB)	Final Cavern Volume (MMB)	% Cavern Change	Leaching Efficiency
BC18	2014	3.51	0.56	18.68	19.23	2.7%	16%
BC102	2017	0.92	0.15	9.45	9.60	1.6%	16%
BH101	2012	0.01	0.002	14.02	14.02	0.0%	16%
BH102	2013	1.47	0.25	12.53	12.78	2.4%	17%
BH104	2012+	2.61	0.41	14.31	14.72	2.8%	16%
BH105	2013	0.02	0.004	13.07	13.08	0.1%	17%
BH106	2015	0.50	0.08	6.83	6.92	1.3%	16%
BH107	2010	1.63	0.27	11.96	12.24	1.7%	17%
BH108	2015	1.66	0.27	10.40	10.67	2.9%	16%
BH109	2015	1.12	0.19	12.14	12.32	1.7%	17%
BH110	2015	0.24	0.04	12.28	12.32	0.0%	17%
BH111	2015	0.06	0.01	13.32	13.33	0.0%	17%
BH114	2013	1.12	0.19	12.55	12.74	1.6%	17%
BM005	1987	0.12	0.02	32.14	32.16	0.1%	17%
BM102	2013	0.41	0.07	11.17	11.23	0.0%	17%
BM103	2016	3.14	0.52	12.16	12.67	4.1%	17%
BM108	2016	2.70	0.44	12.20	12.64	3.3%	16%
BM111	2016+	3.28	0.54	12.42	12.96	4.8%	16%
BM113	2012	0.25	0.04	6.44	6.48	0.6%	16%
BM114	2012	1.16	0.19	9.62	9.80	1.9%	16%
BM115	2011	0.43	0.07	10.56	10.63	0.0%	16%
BM116	2011	1.60	0.26	11.48	11.74	1.7%	16%
WH011	2013+	2.05	0.33	8.07	8.40	4.1%	16%
WH103	2014	1.68	0.27	10.36	10.63	1.9%	16%
WH109	2016	1.70	0.28	11.06	11.33	1.8%	16%
WH111	2015	3.88	0.63	9.15	9.78	6.9%	16%
WH113	2014	0.93	0.15	11.07	11.23	0.9%	16%
WH114	2015	2.90	0.49	10.50	10.99	4.8%	17%

+Sonar in 2018 following 2017 sales/exchange

Shading denotes caverns with more than 3 MMB of injected raw water

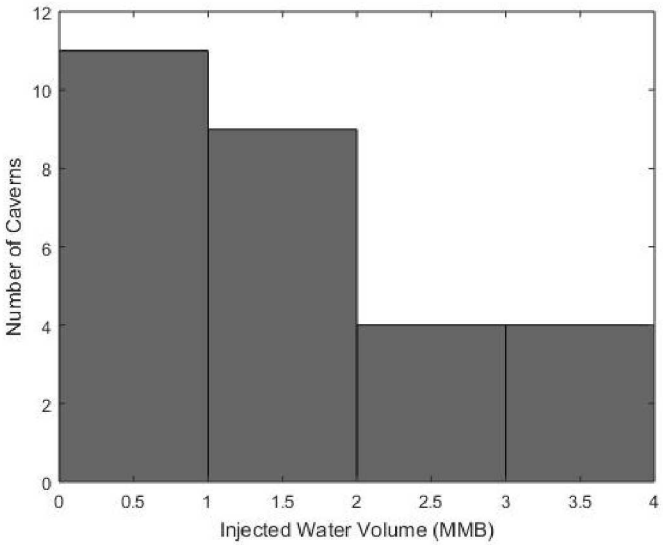

Figure 1-2 Histogram of injected water volumes for 2017, or since last sonar.

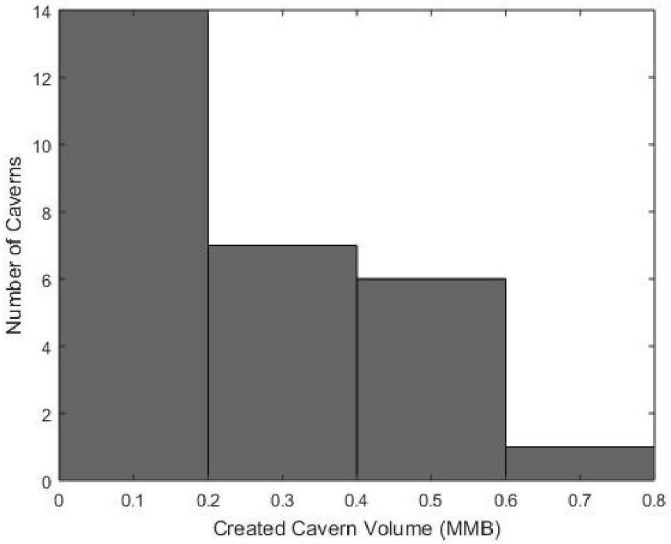

Figure 1-3 Histogram of created cavern volumes for 2017, or since last sonar.

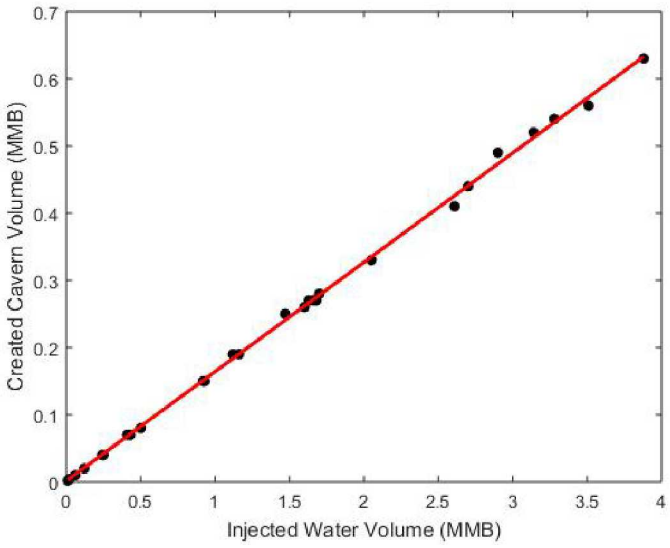

Figure 1-4 Created cavern volume as a function of injected water volume for 2017, or since last sonar.

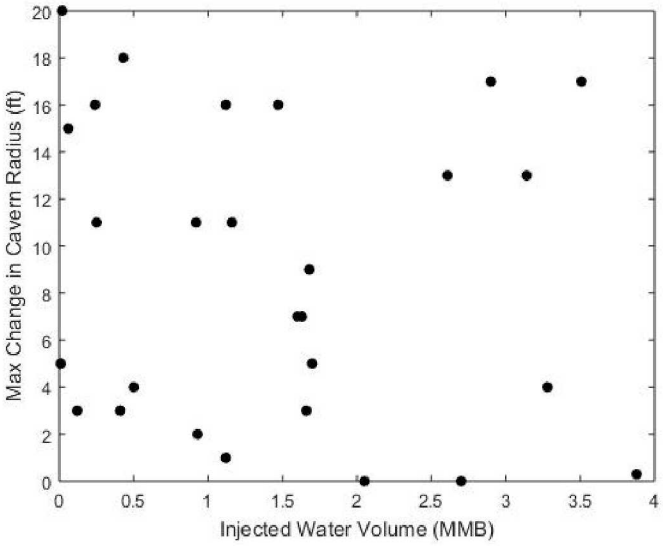

Figure 1-5 Change in cavern radius as a function of injected water volume for 2017, or since last sonar.

2. BACKGROUND ON LEACHING AT SPR

Water is injected into salt caverns to withdraw stored oil. The water is not salt saturated and leaches the cavern walls. Generally, leaching occurs at a depth range in the cavern governed by the water/brine string and oil-brine interface positions. The impact of leaching on cavern shape depends on the type of leaching. There are two leaching types at the Strategic Petroleum Reserve (SPR), drawdown or conventional, as illustrated in Figure 2-1.

2.1. Drawdown Leaching

Drawdown leaching involves leaching due to the injection of water through the hanging string which pushes oil out the top of the cavern (Figure 2-1, 1A). If the volume of withdrawn oil is then replaced, in part or whole, the process is considered Daisy Chain leaching for repeated cycles of oil withdrawal and fill (Figure 2-1, 1B). Drawdown leaching is now the most common type of leaching in use at SPR. Leaching performed during 2017 was drawdown leaching and included withdrawal for oil sales and daisy chain for exchanges. Daisy chain leaches are a sequence of oil withdrawal and fills. In this report, all the leaching is modeled as withdrawal and any oil transferred into the SPR for exchanges during 2017 is not accounted for.

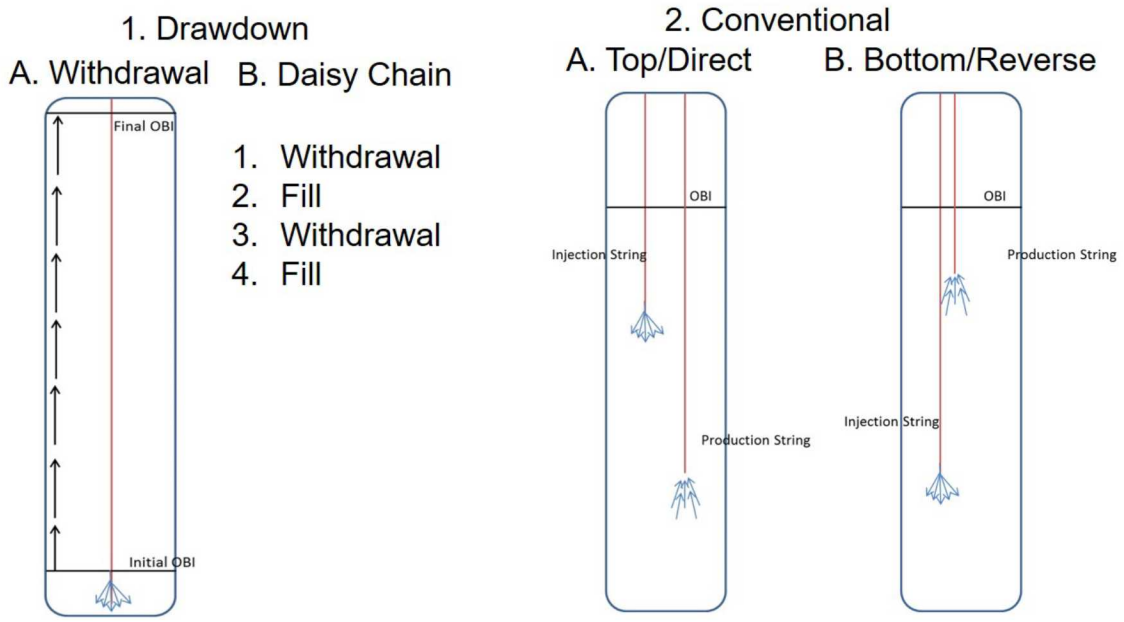

Figure 2-1 Leaching styles at SPR from Lord, D. L. et al. (2013).

2.2. Conventional Leaching

Conventional leaching was more commonly used as the caverns were developed. Conventional leaching involves two strings, one for production and one for injection. If the injection string is positioned above the production string during leaching the process is called top or direct leaching (Figure 2-1, 2A). Alternatively, if the injection string is

positioned below the production string the process is called bottom or reverse leaching (Figure 2-1, 2B). Conventional leaching was not used in 2017.

3. SANSMIC LEACHING MODEL

3.1. History

Leach effects are modeled with the **San**dia **S**olution **Mi**ning **C**ode (SANSMIC) (Russo, 1981). SANSMIC was developed in the early 1980's to model the effects of leaching on the cavern shape and volume. The code uses standard salt dissolution models that account for the original salinity of the water, temperature and flow velocity (Russo, 1981). Simulations use sonar derived cavern shapes at the start of each leaching stage, the actual casing depths, and the field reported flow quantities for water. Then the model computes the effects of leaching on cavern shape and volume, treating the cavern as axisymmetric and limiting leaching to cavern depths below the oil-brine interface (OBI). The model assumes tall, slender and cylindrical cavern shapes and allows for the OBI to move.

SANSMIC was validated for conventional leach (both direct and reverse) capabilities by comparison with cavern creation data (Eyermann, 1984). Subsequent comparisons between SANSMIC modeled cavern geometries and sonar measurements following the 2011 oil sale and subsequent remedial leach activities indicated the simulated cavern radius is within 5% of the measured cavern radius and the leached volumes are within 10% (Lord et al., 2012). A re-validation of SANSMIC in withdrawal, direct and reverse leach modes for Phase II and III caverns indicated that simulated radial profiles match sonar observations within 1.5% - 12 % and the observed leach volume was simulated within 1% -13% (Weber et al., 2014).

3.2. Expected Patterns

SANSMIC predicts that leaching of the cavern due to drawdown results in the largest radial growth at the depth of the hanging string and that growth tapers *up* to the depth of the OBI as shown in Figure 3-1 (Lord et al., 2012; Eldredge et al., 2013; Weber et al., 2013; Weber et al., 2014; Weber et al., 2017). This pattern reflects the concentration of salt in the injected water over time, with the lowest salt concentration near the injection point of the raw water (the hanging string depth). The water with the lowest salt concentration will produce the greatest leaching of the salt walls and corresponding radial growth of the cavern. Thus, the most radial growth for the drawdown leaching style is at the depth of the hanging string, as shown by the difference in position between the pre-drawdown geometry (blue dashed line) and the SANSMIC predicted post-drawdown geometry (black line) in Figure 3-1 for Bryan Mound cavern 116. The starting (green dashed line) and final (red dashed line) positions of the OBI are also included to show the vertical range of the leached zone. The vertical black line is the hanging string.

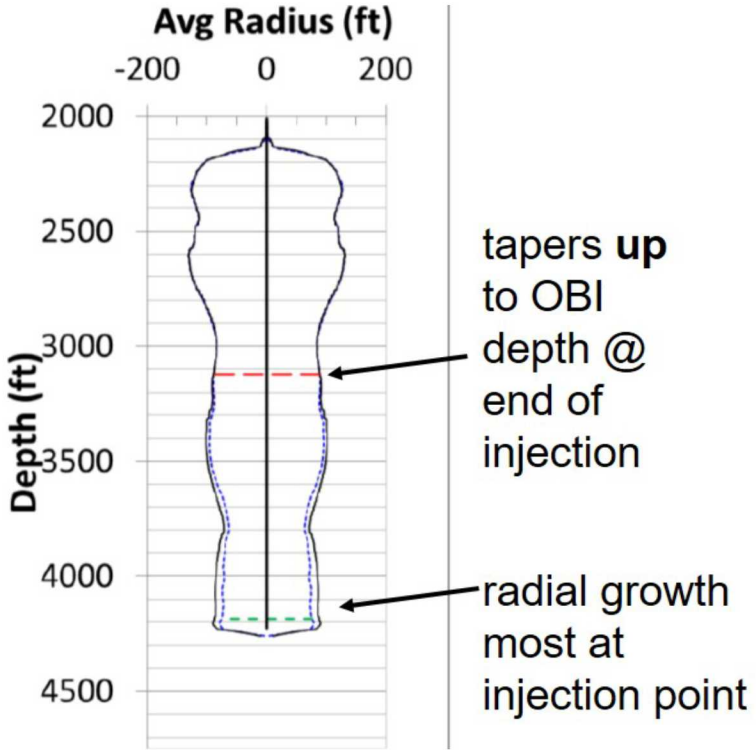

Figure 3-1 Example of drawdown leaching of Bryan Mound cavern 116 from Eldredge et al., 2013

In conventional leaching, cavern radial growth is greatest at the depth of the injection string and tapers *down* to the depth of the production string (Figure 3-2). This contrasts the tapering *up* from the injection point to the OBI expected for drawdown leaching. Figure 3-2 shows a comparison of the sonar profiles before (blue line) and after (green line) conventional leaching demonstrating the change in cavern shape associated with a 2012 leach to completion effort.

Considering the leaching from the 2017 oil sales and exchanges was completely in drawdown mode, the leaching patterns predicted by SANSMIC will show the greatest radial growth at the location of the injection point or hanging string depth which will taper up to the final OBI depth at the end of injection.

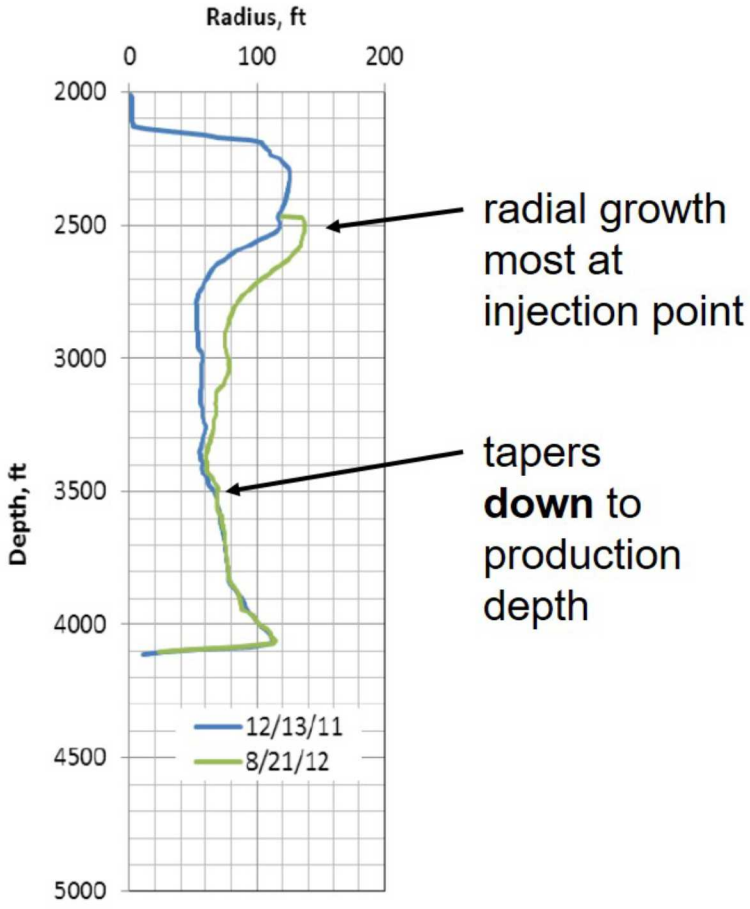

Figure 3-2 Example of conventional leaching of Bryan Mound cavern 113 from Eldredge et al., 2013

4. SUMMARY OF INJECTED WATER IN 2017

Daily raw water injection amounts are taken from CAVEMAN and summed to calculate the total amount of injected raw water. The water injections into each cavern during 2017, and/or since the last sonar in the cavern, are summarized in Table 4-1 through Table 4-4. Four caverns have had more than 3 MMB of water injected since the last sonar: BC18, BM103, BM111, and WH111. Sandia recommends sonar surveys after every 3 MMB of injected water (Lord et al., 2011).

4.1. Bayou Choctaw

Bayou Choctaw (BC) had 2 caverns with raw water injections in 2017 as shown in Table 4-1. One cavern, BC18, has had more than 3MMB of water injected.

Table 4-1 Summary of injected water in 2017, or since last sonar, at BC

Cavern	Latest sonar	Dates of water inject	Injected Water Volume (MMB)
BC18	2014	9/2/2017-9/29/2017*	3.51
BC102	2017	9/3/2017-9/29/2017*	0.92

*denotes intermittent flow during these dates
Shading denotes caverns with more than 3 MMB of injected raw water

The daily water injection volumes for each BC cavern with raw water movement since the last sonar are plotted over time in Figure 4-1 to Figure 4-2. The data are divided into stages and the time average for each stage is also plotted.

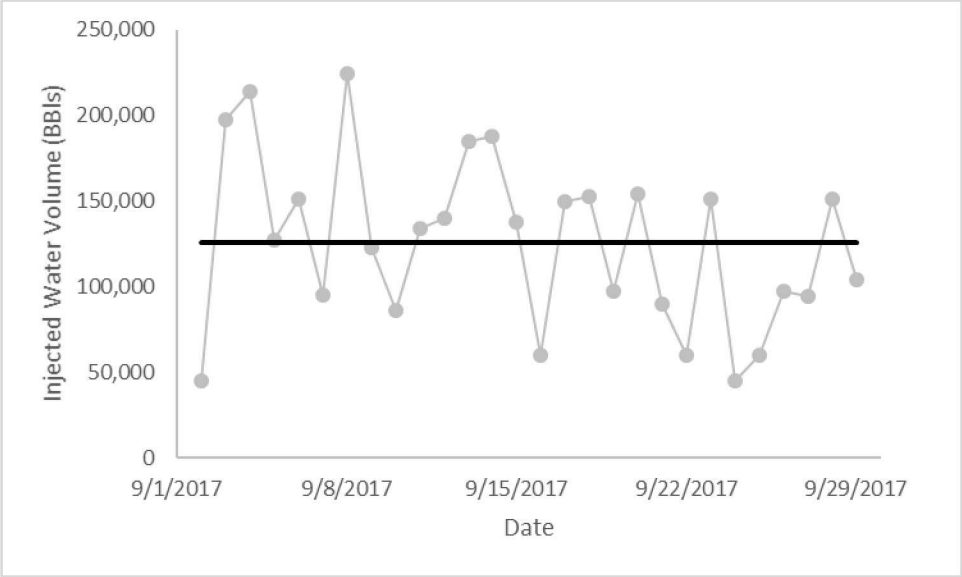

Figure 4-1 Daily measured (gray) and average (black) injected water volumes for BC18.

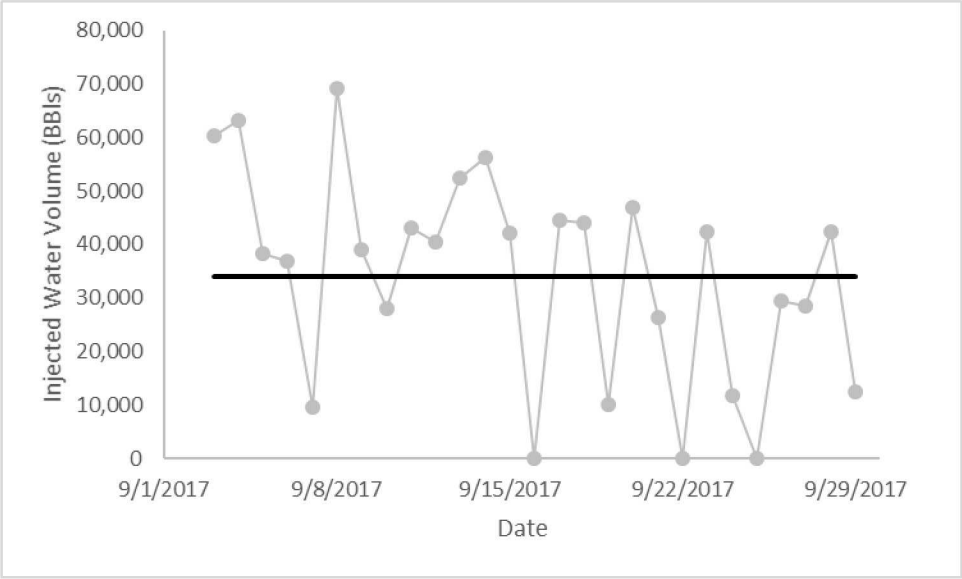

Figure 4-2 Daily measured (gray) and average (black) injected water volumes for BC102.

4.2. Big Hill

Big Hill (BH) had 11 caverns with raw water injections in 2017 as shown in Table 4-2. No caverns have had more than 3MMB of water injected.

Table 4-2 Summary of injected water in 2017, or since last sonar, at BH

Cavern	Latest sonar	Dates of water inject	Injected Water Volume (MMB)
BH101	2012	12/8/2017-12/9/2017	0.10
BH102	2013	6/13/2013-7/8/2013 8/31/2013-9/4/2013 1/8/2015-1/11/2015 2/25/2017-5/7/2017* 11/29/2017-12/2/2017*	1.47
BH104	2012+	1/29/2013-2/16/2013 2/25/2017-5/7/2017* 11/29/2017	2.61
BH105	2013	2/25/2017-5/7/2017* 12/1/2017-12/2/2017	0.02
BH106	2015	11/9/2017-12/7/2017	0.50
BH107	2010	12/22/2015-12/23/2015 4/29/2017-6/9/2017* 11/5/2017-12/1/2017*	1.63
BH108	2015	4/30/2017-6/2/2017* 11/5/2017-12/1/2017*	1.66
BH109	2015	5/1/2017-6/8/2017*	1.12

		11/5/2017-11/29/2017*	
BH110	2015	5/9/2017-5/27/2017* 11/5/2017	0.02
BH111	2015	3/25/2017-4/1/2017* 11/29/2017-12/2/2017*	0.06
BH114	2013	1/11/2016-1/14/2016 2/25/2017-5/7/2017* 11/29/2017	1.12

+Sonar in 2018 following 2017 sales/exchange
*denotes intermittent flow during these dates
Shading denotes caverns with more than 3 MMB of injected raw water

The daily water injection volumes for each BH cavern with raw water movement since the last sonar are plotted over time in Figure 4-3 to Figure 4-13. The data are divided into stages and the time average for each stage is also plotted.

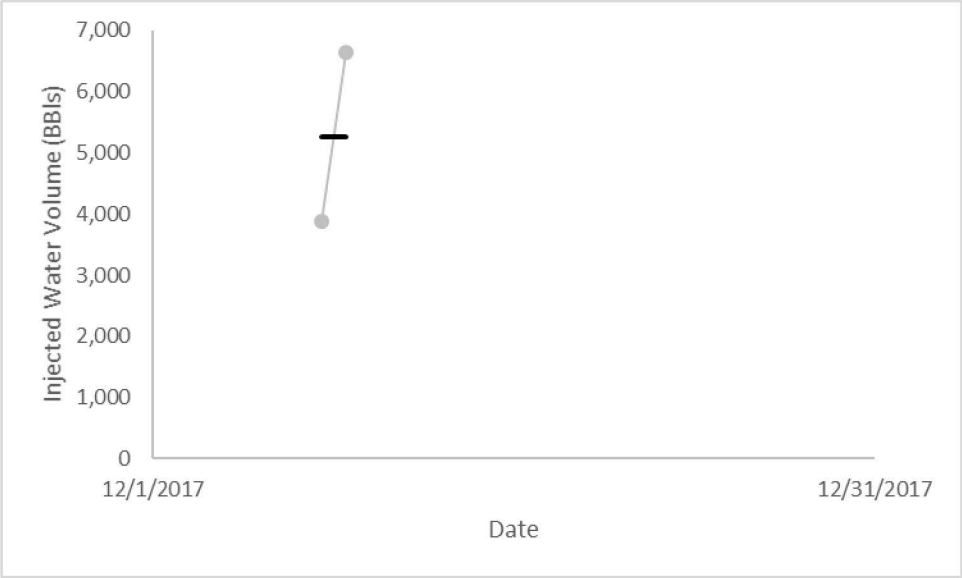

Figure 4-3 Daily measured (gray) and average (black) injected water volumes for BH101.

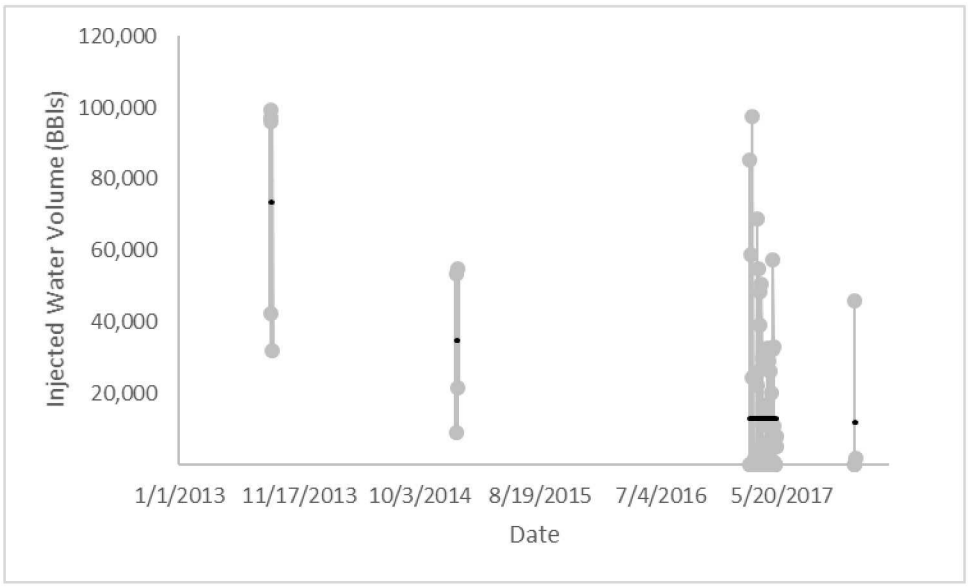

Figure 4-4 Daily measured (gray) and average (black) injected water volumes for BH102.

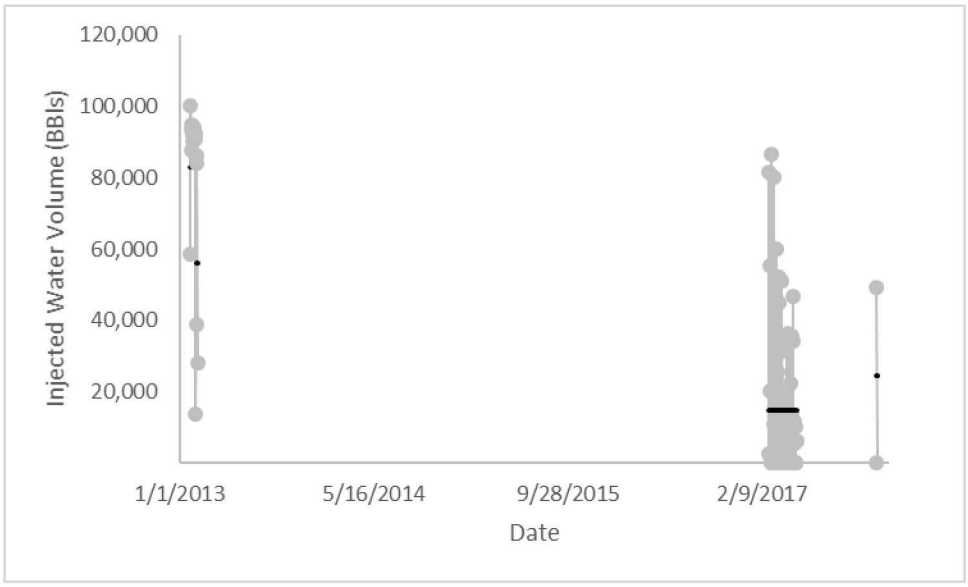

Figure 4-5 Daily measured (gray) and average (black) injected water volumes for BH104.

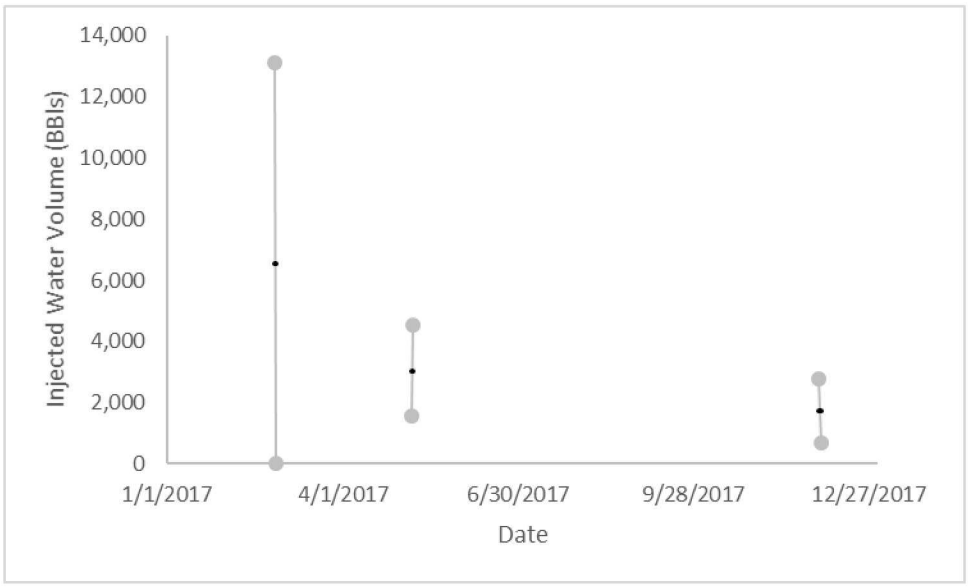

Figure 4-6 Daily measured (gray) and average (black) injected water volumes for BH105.

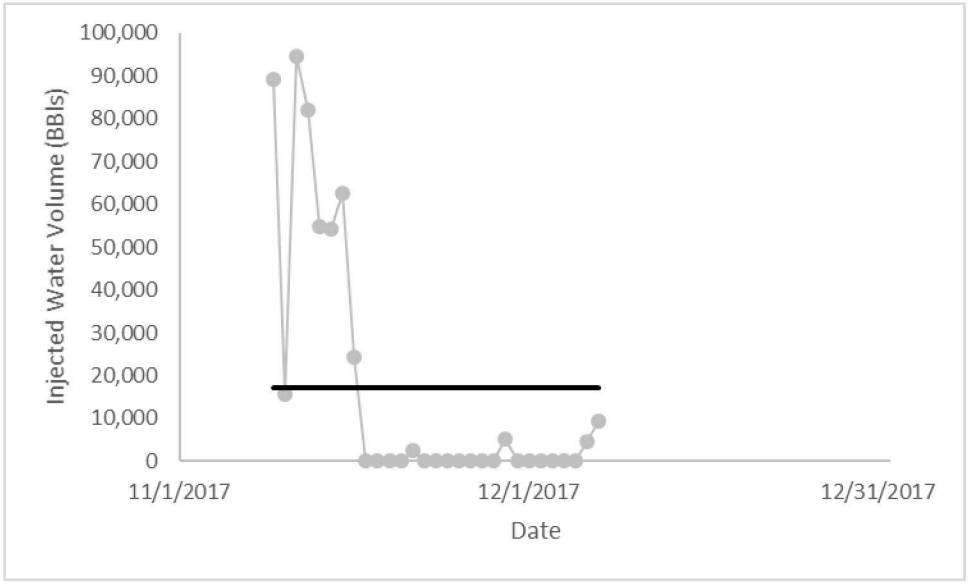

Figure 4-7 Daily measured (gray) and average (black) injected water volumes for BH106.

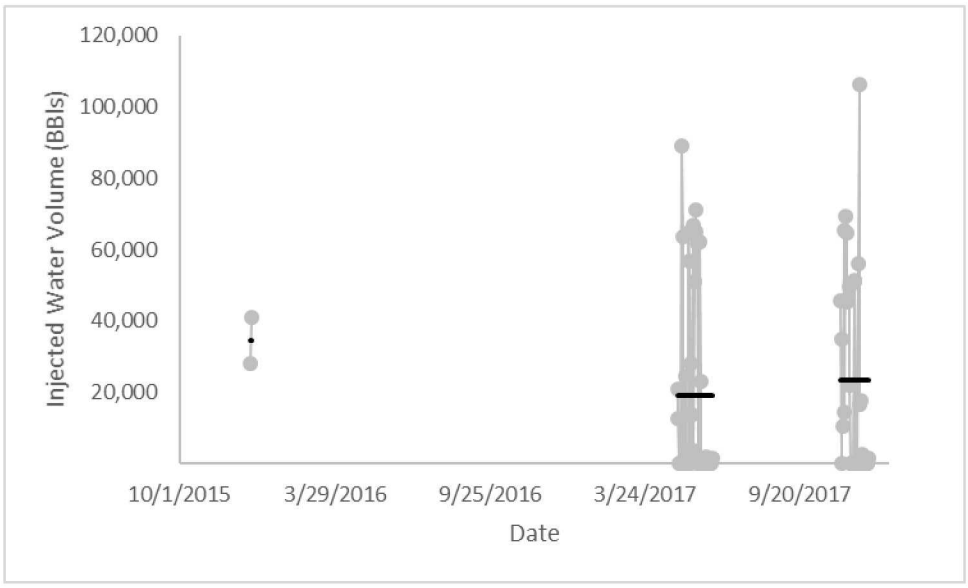

Figure 4-8 Daily measured (gray) and average (black) injected water volumes for BH107.

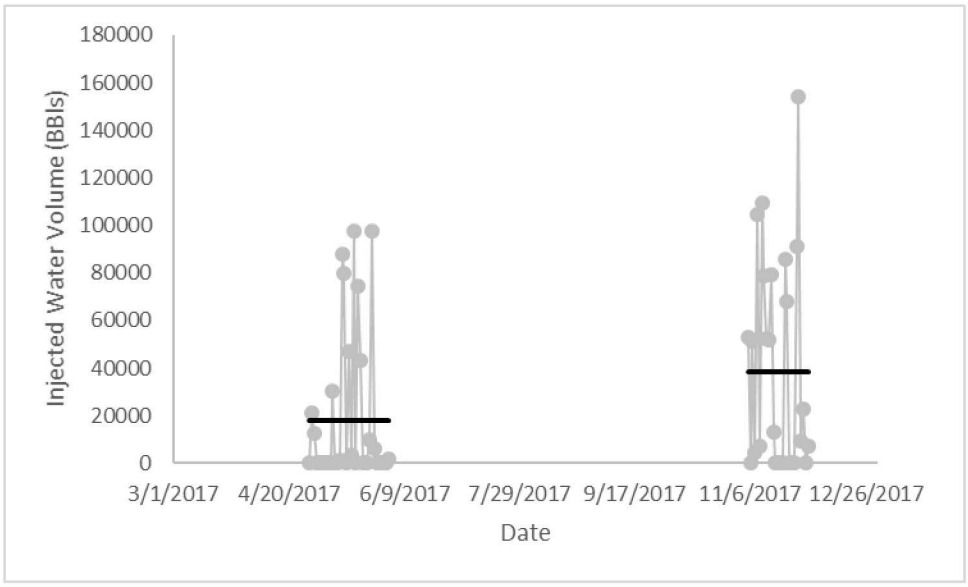

Figure 4-9 Daily measured (gray) and average (black) injected water volumes for BH108.

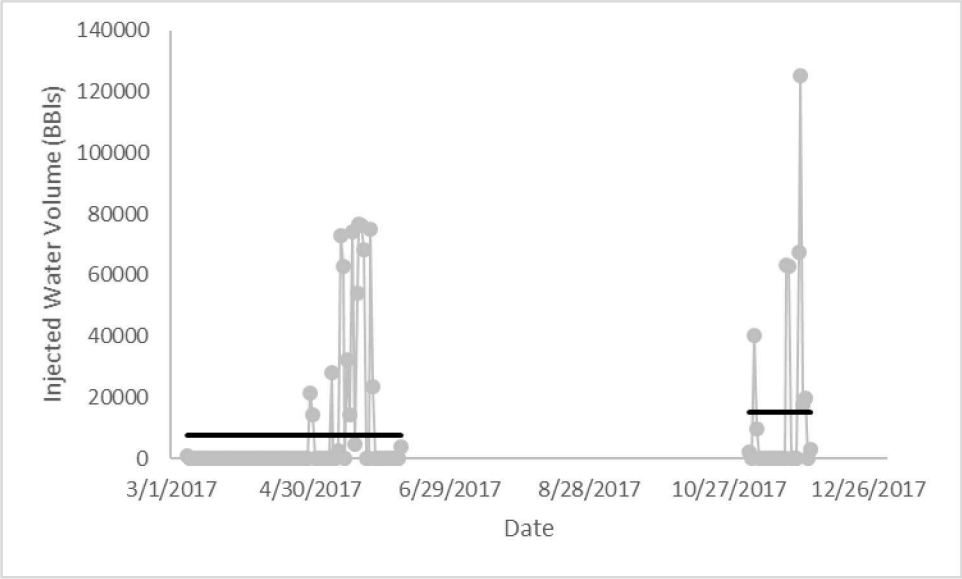

Figure 4-10 Daily measured (gray) and average (black) injected water volumes for BH109.

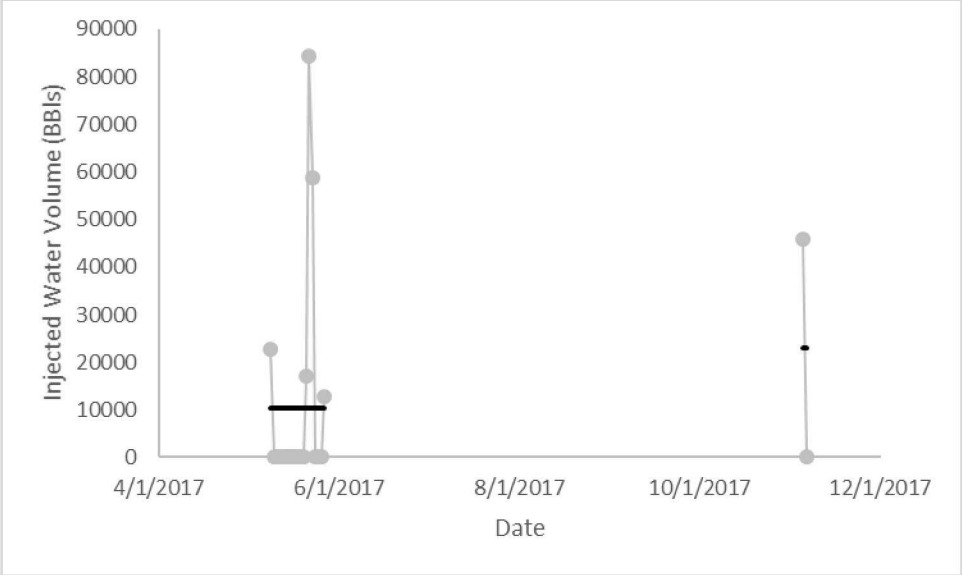

Figure 4-11 Daily measured (gray) and average (black) injected water volumes for BH110.

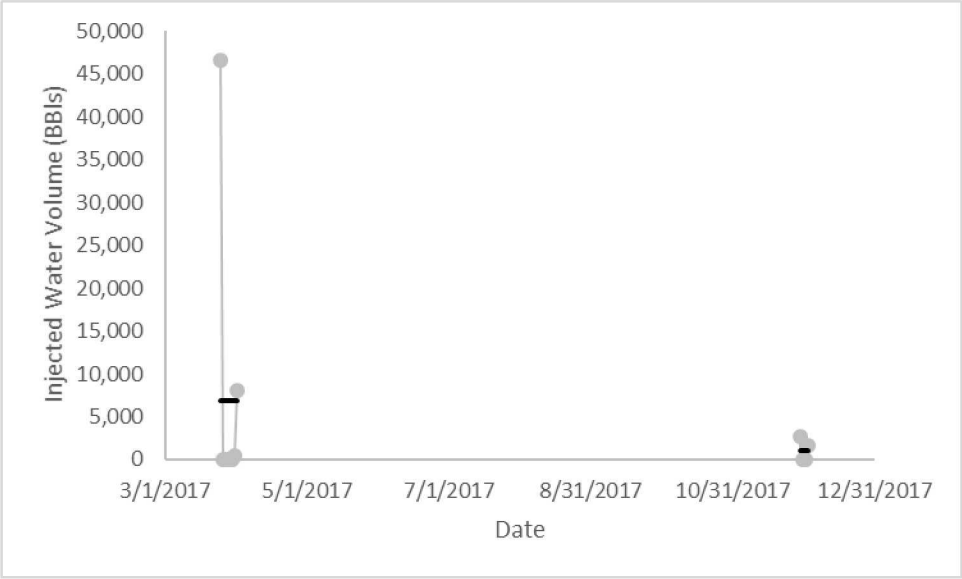

Figure 4-12 Daily measured (gray) and average (black) injected water volumes for BH111.

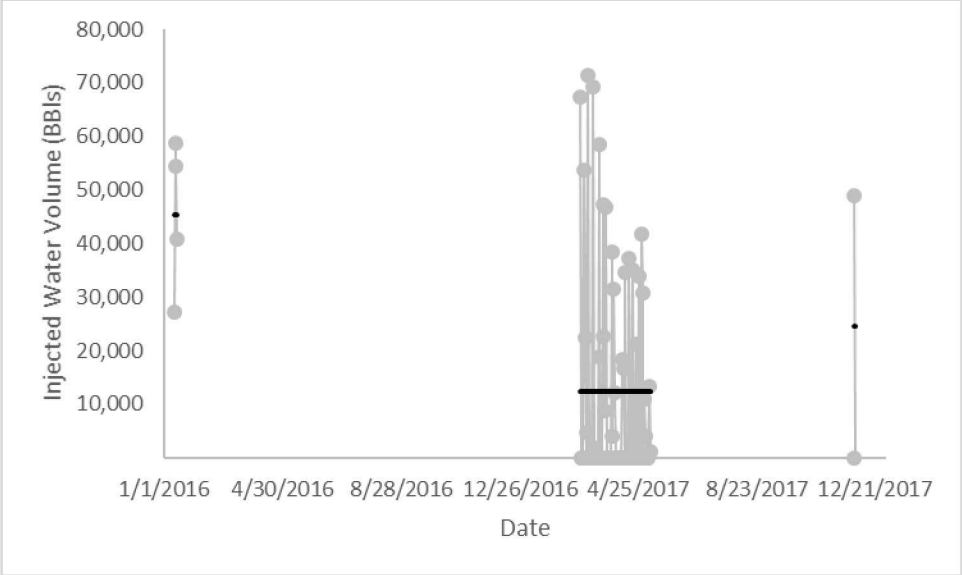

Figure 4-13 Daily measured (gray) and average (black) injected water volumes for BH114.

4.3. Bryan Mound

Bryan Mound (BM) had 9 caverns with raw water injections in 2017 as shown in Table 4-3. Two caverns, BM103 and BM111, have had more than 3MMB of water injected.

Table 4-3 Summary of injected water in 2017, or since last sonar, at BM

Cavern	Latest sonar	Dates of water inject	Injected Water Volume (MMB)
BM005	1987^	3/25/2017-3/29/2017 6/8/2017-6/9/2017	0.01
BM102	2013	10/15/2017 – 10/30/2017*	0.41
BM103	2016	4/27/2017-7/2/2017* 10/4/2017-11/30/2017*	3.14
BM108	2016	5/4/2017-7/2/2017* 10/4/2017-11/30/2017*	2.70
BM111	2016+	5/4/2017-7/2/2017* 10/4/2017-11/30/2017*	3.28
BM113	2012	4/16/2017-5/3/2017*	0.25
BM114	2012	1/19/2012-1/27/2012 4/16/2017-4/27/2017* 11/26/2017	1.16
BM115	2011	4/16/2017-5/3/2017* 11/26/2017-12/10/2017*	0.43
BM116	2011	8/30/2012-9/12/2012 12/13/2012-1/4/2013 4/16/2017-4/27/2017*	1.60

^last full sonar
+Sonar in 2018 following 2017 sales/exchange
*denotes intermittent flow during these dates
Shading denotes caverns with more than 3 MMB of injected raw water

The daily water injection volumes for each BM cavern with raw water movement since the last sonar are plotted over time in Figure 4-14 to Figure 4-22. The data are divided into stages and the time average for each stage is also plotted.

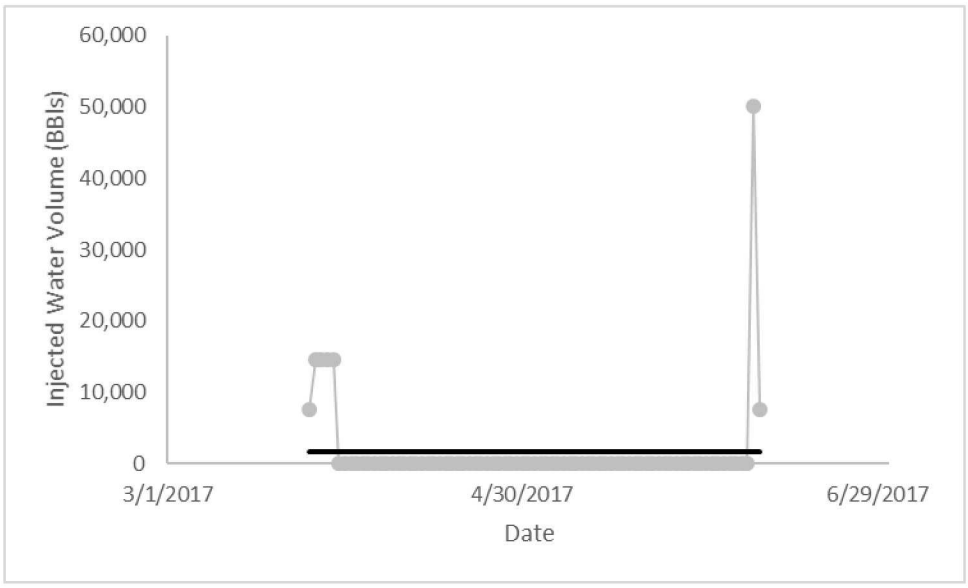

Figure 4-14 Daily measured (gray) and average (black) injected water volumes for BM005.

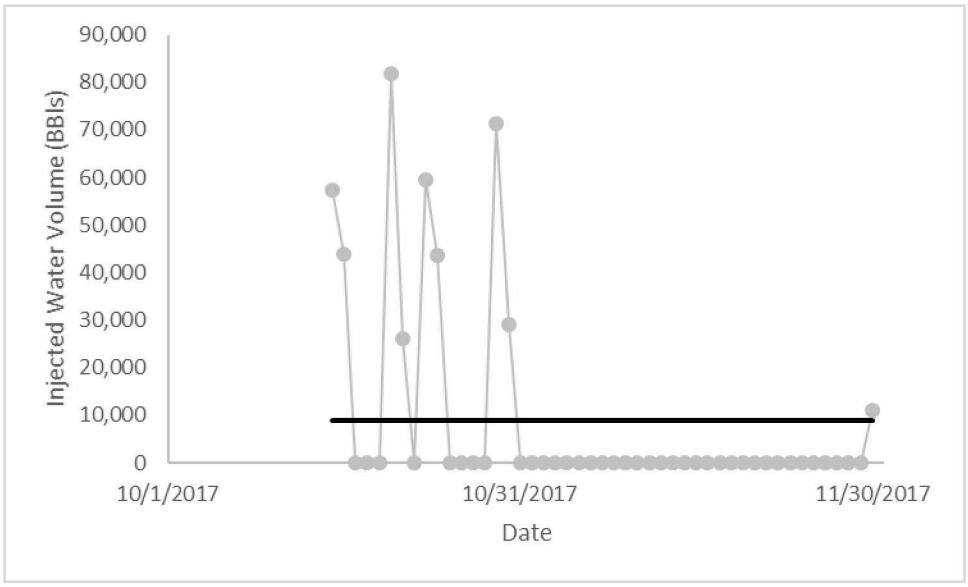

Figure 4-15 Daily measured (gray) and average (black) injected water volumes for BM102.

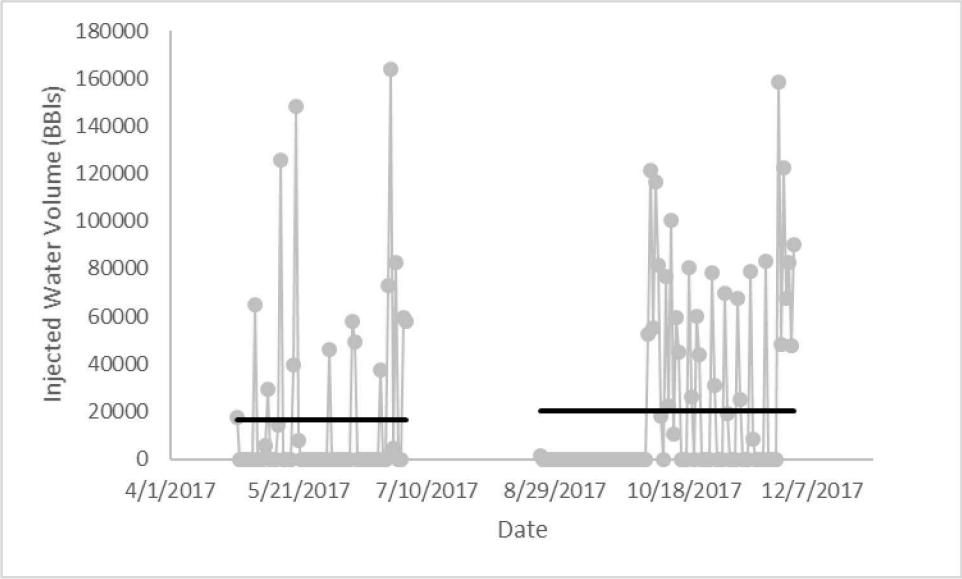

Figure 4-16 Daily measured (gray) and average (black) injected water volumes for BM103.

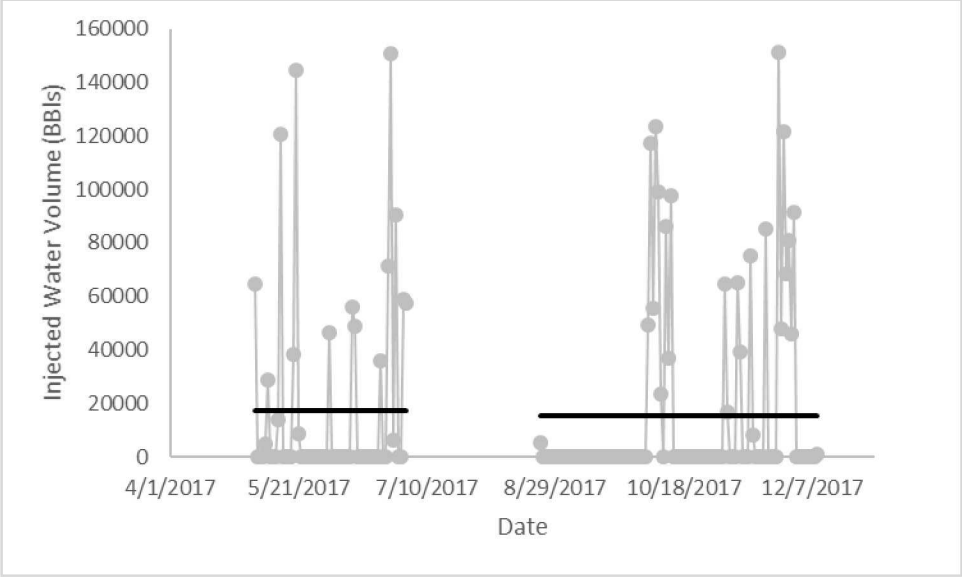

Figure 4-17 Daily measured (gray) and average (black) injected water volumes for BM108.

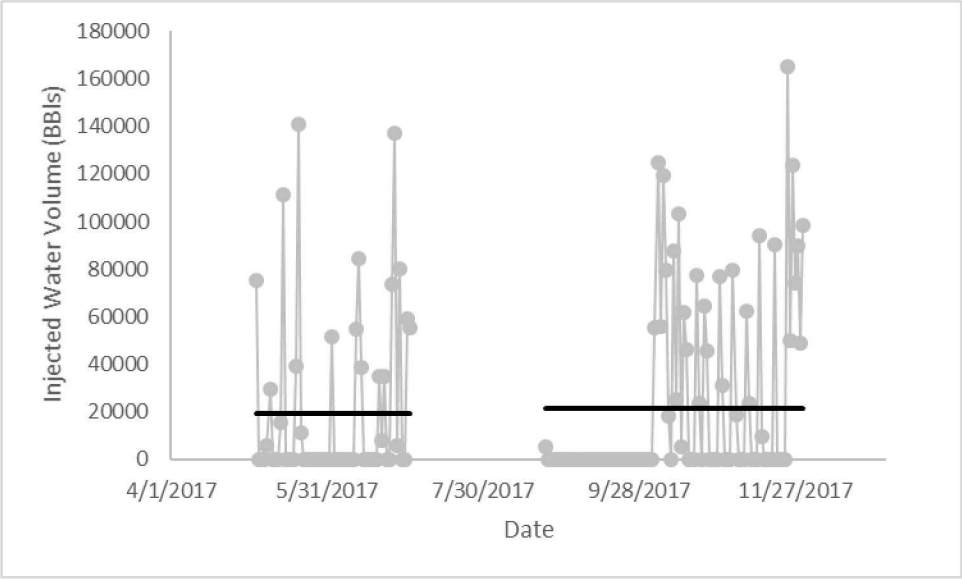

Figure 4-18 Daily measured (gray) and average (black) injected water volumes for BM111.

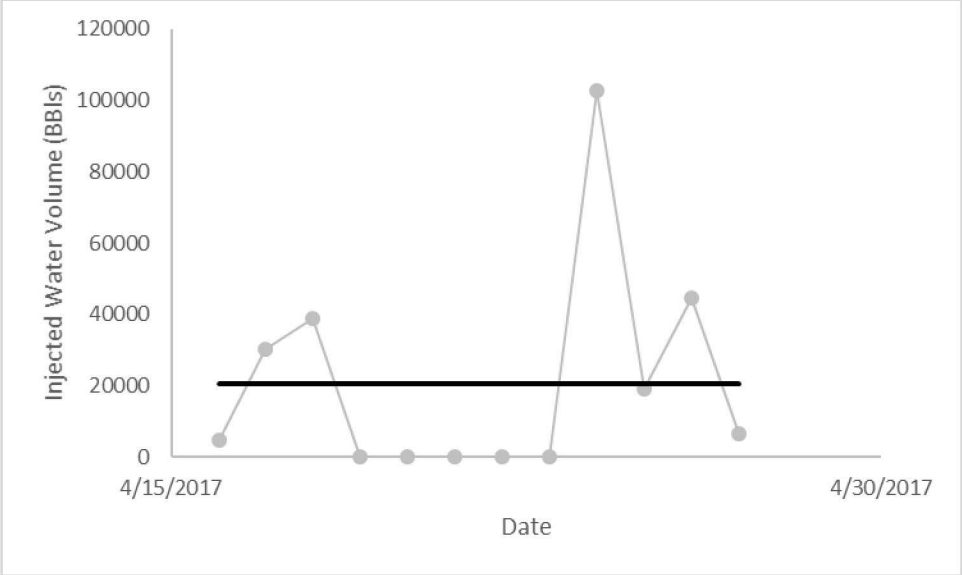

Figure 4-19 Daily measured (gray) and average (black) injected water volumes for BM113.

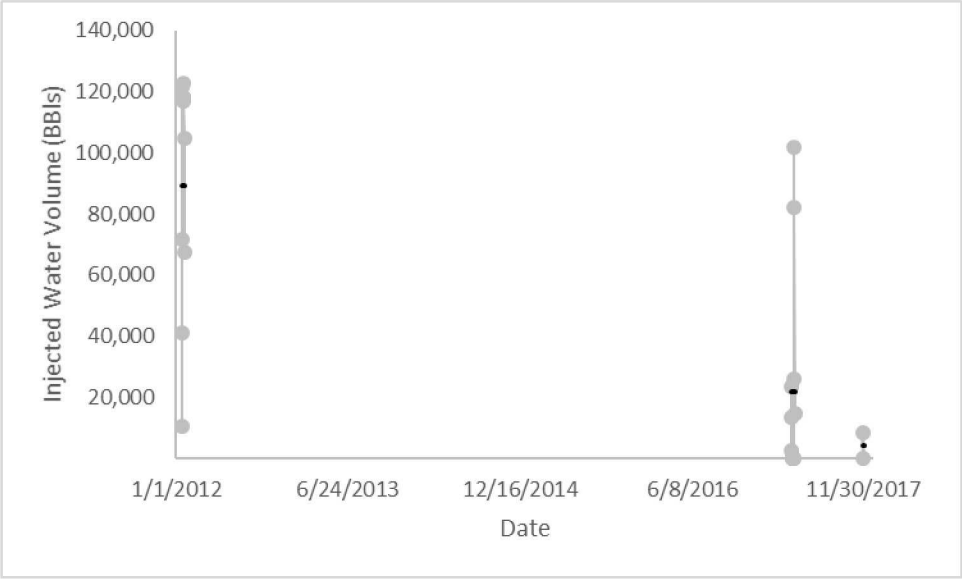

Figure 4-20 Daily measured (gray) and average (black) injected water volumes for BM114.

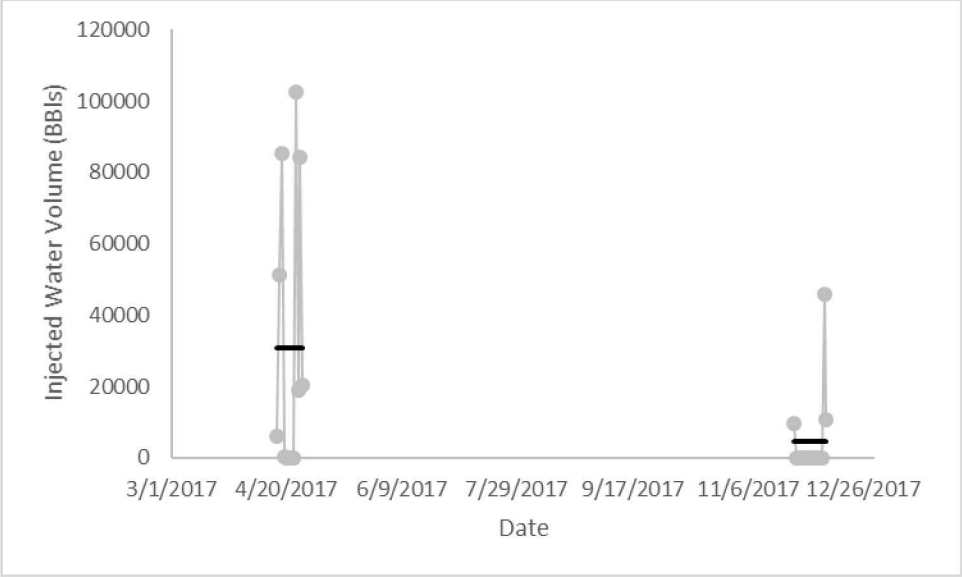

Figure 4-21 Daily measured (gray) and average (black) injected water volumes for BM115.

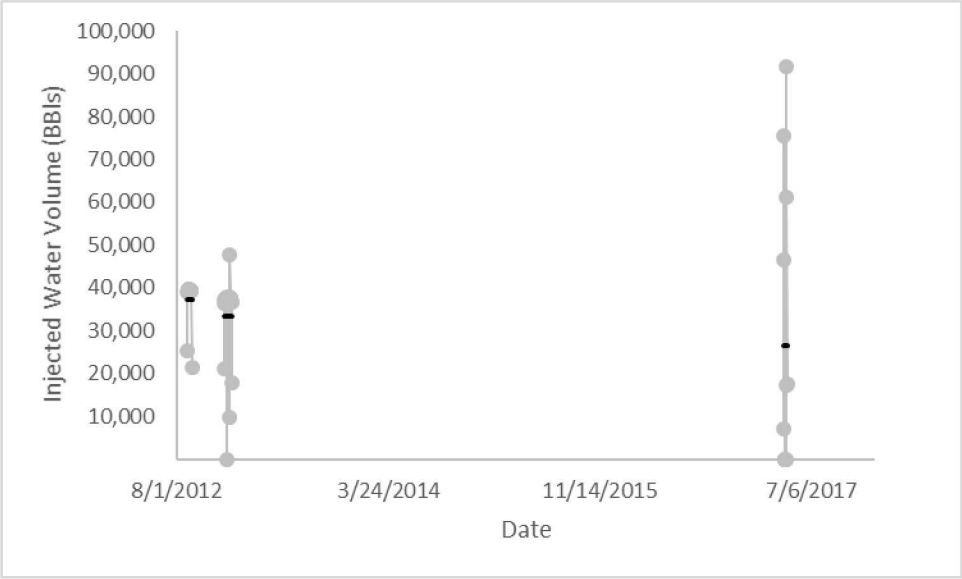

Figure 4-22 Daily measured (gray) and average (black) injected water volumes for BM116.

4.4. West Hackberry

West Hackberry (WH) had 6 caverns with raw water injections in 2017 as shown in Table 4-4. One cavern, WH111, has had more than 3MMB of water injected. Two additional caverns, WH106 and WH115, have had raw water movement since the last sonar but are not included here as they did not have water movement in 2017.

Table 4-4 Summary of injected water in 2017, or since last sonar, at WH

Cavern	Latest sonar	Dates of water inject	Injected Water Volume (MMB)
WH011	2013+	4/2/2014-4/9/2014 5/19/2017-7/23/2017*	2.05
WH103	2014	1/17/2016-1/27/2016 3/2/2017-4/25/2017* 8/31/2017-9/3/2017	1.68
WH109	2016	4/25/2017-5/5/2017* 8/12/2017-12/29/2017*	1.70
WH111	2015	3/15/2017-3/19/2017 5/19/2017-7/1/2017* 9/3/2017-12/1/2017*	3.88
WH113	2014	3/2/2017-4/25/2017* 8/31/2017-9/3/2017 12/29/2017–12/31/2017*	0.93
WH114	2015	4/25/2017-7/1/2017* 8/18/2017-12/29/2017*	2.90

+Sonar in 2018 following 2017 sales/exchanges
*denotes intermittent flow during these dates
Shading denotes caverns with more than 3 MMB of injected raw water

The daily water injection volumes for each WH cavern with raw water movement since the last sonar are plotted over time in Figure 4-23 to Figure 4-28. The data are divided into stages and the time average for each stage is also plotted.

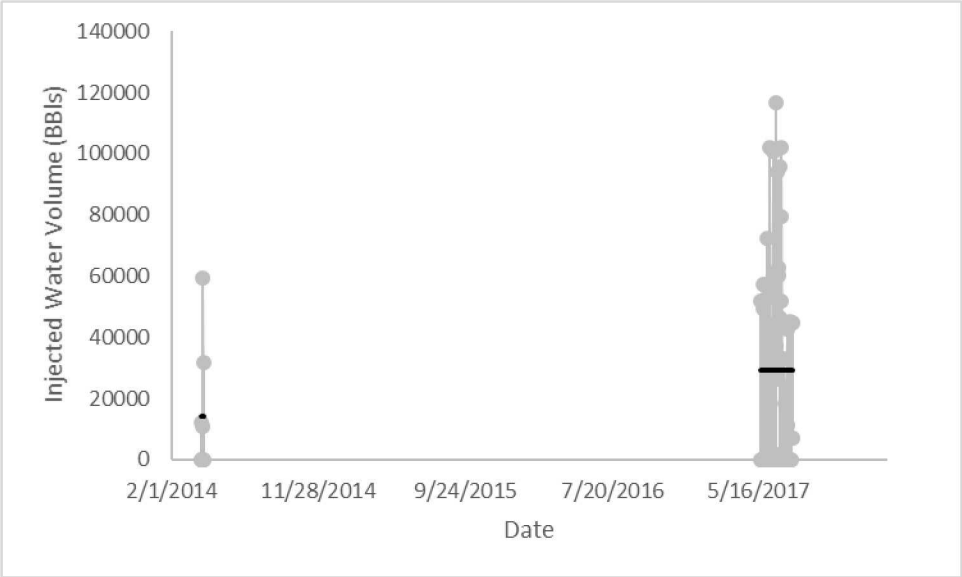

Figure 4-23 Daily measured (gray) and average (black) injected water volumes for WH011.

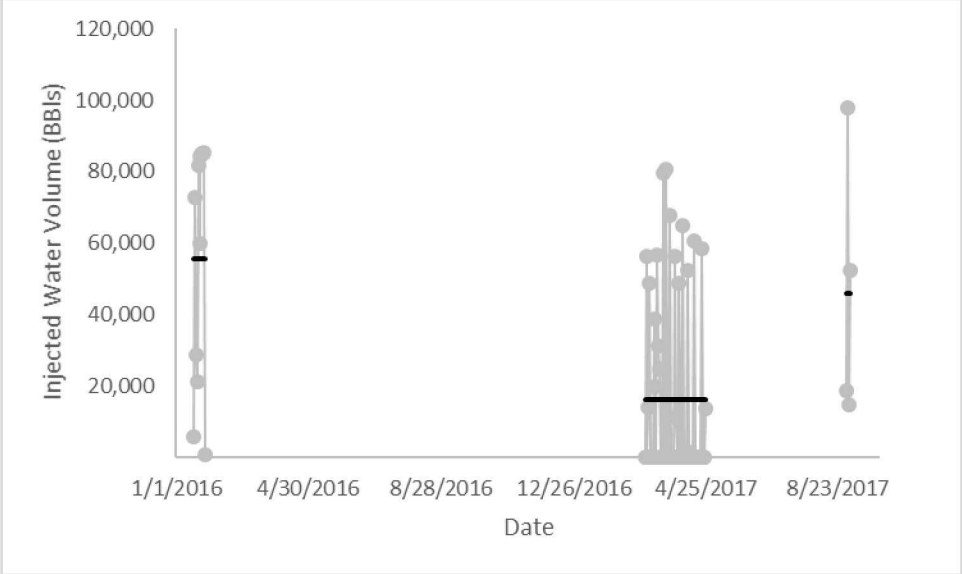

Figure 4-24 Daily measured (gray) and average (black) injected water volumes for WH103.

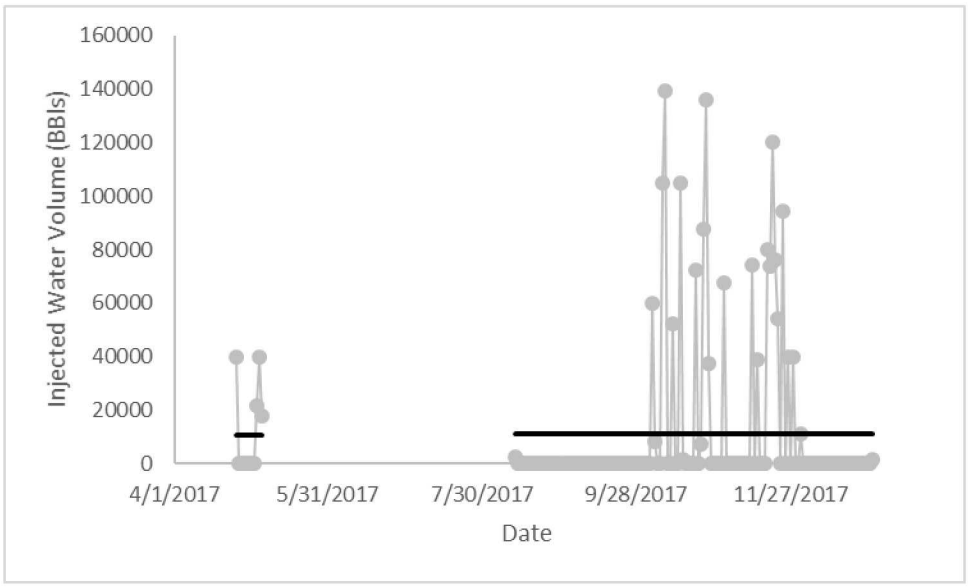

Figure 4-25 Daily measured (gray) and average (black) injected water volumes for WH109.

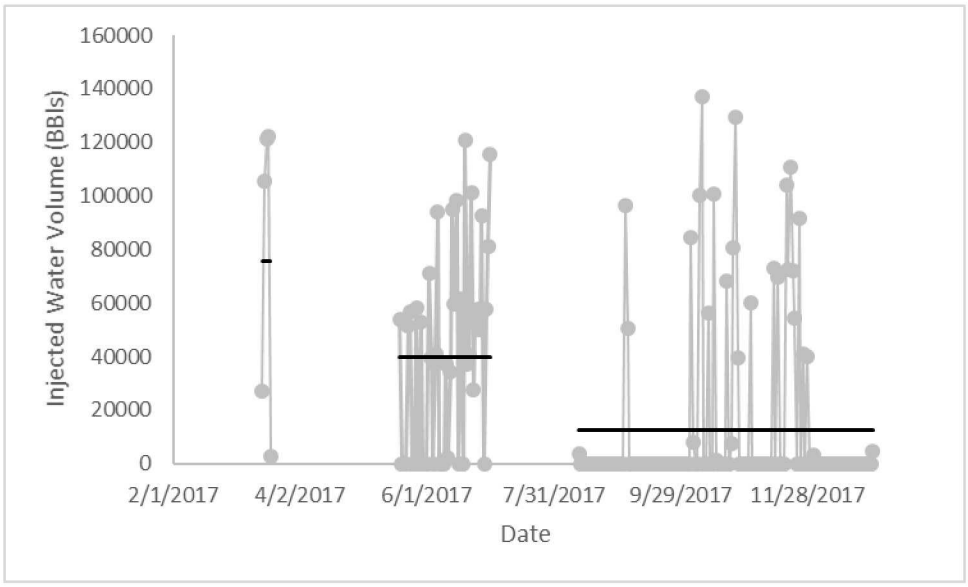

Figure 4-26 Daily measured (gray) and average (black) injected water volumes for WH111.

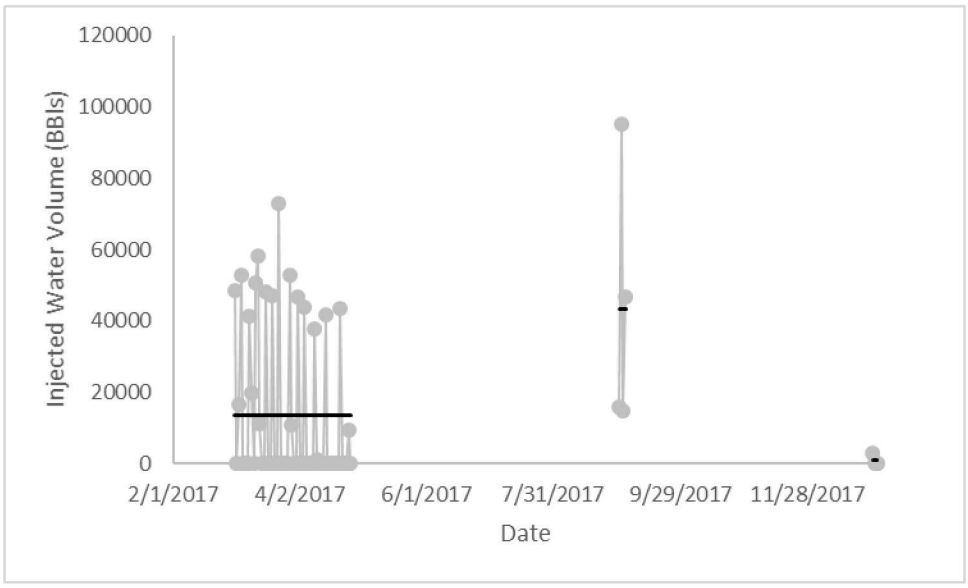

Figure 4-27 Daily measured (gray) and average (black) injected water volumes for WH113.

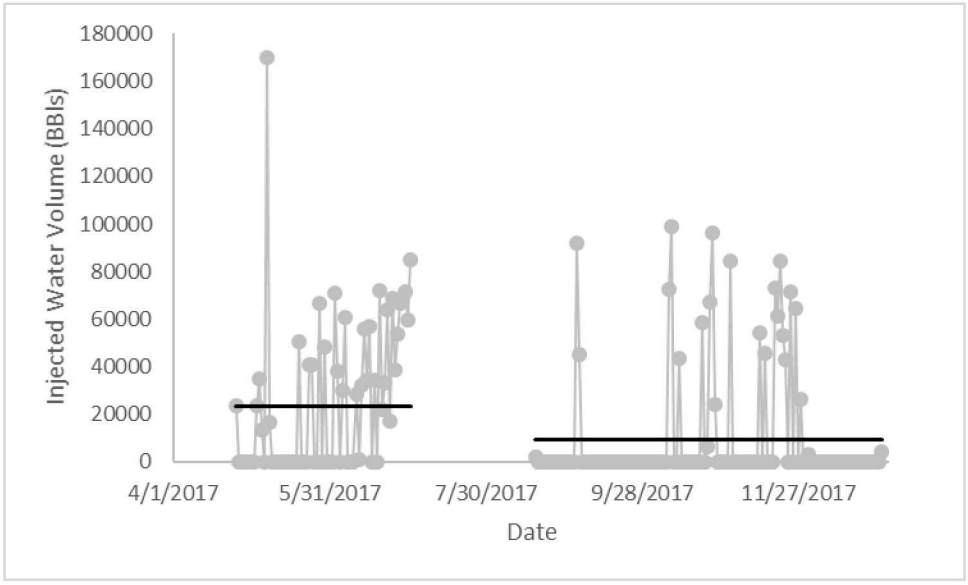

Figure 4-28 Daily measured (gray) and average (black) injected water volumes for WH114.

5. SIMULATED CAVERN GEOMETRIES AND VOLUMES

SANSMIC simulations start from a known cavern geometry, hanging string and oil brine interface depths, and injected water volumes. The cavern geometry is usually taken as the last sonar prior to injection. A 2-D, axisymmetric representation of the cavern geometry with an equivalent cavern volume is then calculated and used as the initial geometry. The hanging string and oil brine interface depths are taken from the daily site reports, however they are included in SANSMIC as a distance above the cavern floor, herein called a rise, rather than a depth. The daily raw water injection amounts are taken from CAVEMAN and stages of water injection are identified. For each stage (period of time), an average injection rate is calculated from the daily rates over the stage duration. Leaching occurs during and after injection, called the workover (WO) period. The workover period is generally chosen as 60 days to ensure the simulations have enough time to reach equilibrium as indicated by the specific gravity of the fluid in the outlet reaching 1.2, the expected value for salt saturated water (temperature dependent).

5.1. Bayou Choctaw

Simulation results for Bayou Choctaw are summarized in Table 5-1. One cavern at this site, BC18, has had more than 3MMB of water injected since the last sonar.

Table 5-1 Summary of Simulation Results for Bayou Choctaw

Cavern	Latest sonar	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Maximum Change in Radius (ft)
BC18	2014	3.51	0.56	17
BC102	2017	0.92	0.15	2

Shading denotes caverns with more than 3 MMB of injected raw water

5.1.1. BC18

BC18 had significant water movement in 2017 (see Table 4-1) which is modeled in one stage summarized in Table 5-2. The average injection rate was 125,408 BBls/day over the 28 days of injection. A workover of 120 days was used to finish the first stage. The cumulative injected water volume is shown as a function of time in Figure 5-1. The hanging string was located at 120 ft above the cavern bottom. The initial OBI was 135 ft above the cavern bottom. The evolution of the OBI over time is shown in Figure 5-2.

Table 5-2 Summary of Simulation Input for BC18

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2110	4210	2100	120	135	125408	28	120

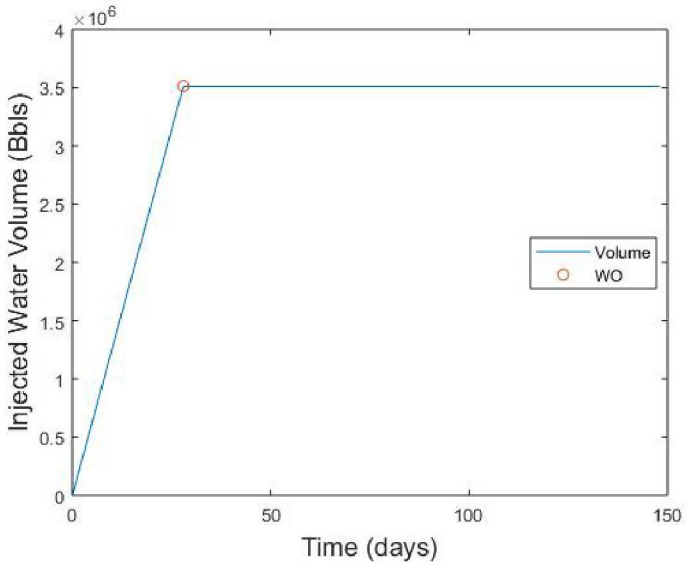

Figure 5-1 Injected water time history for BC18 simulation.

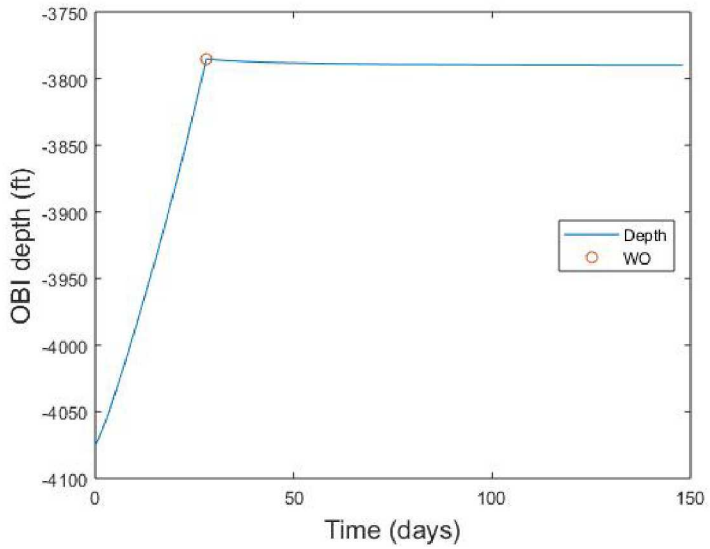

Figure 5-2 OBI depth time history for BC18 simulation.

The outlet specific gravity reached 1.1997, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the workover. As summarized in Table 5-3, the total amount of raw water injected was 3.51 MMB creating a volume of 0.56 MMB by leaching over 420 ft of the cavern wall out to 17 ft.

Table 5-3 Summary of Simulation Output for BC18

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1997	3.51	0.56	420	17

The simulated cavern shape as a result of the leaching is shown in Figure 5-3. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2014 sonar and the final geometry (red line) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-4.

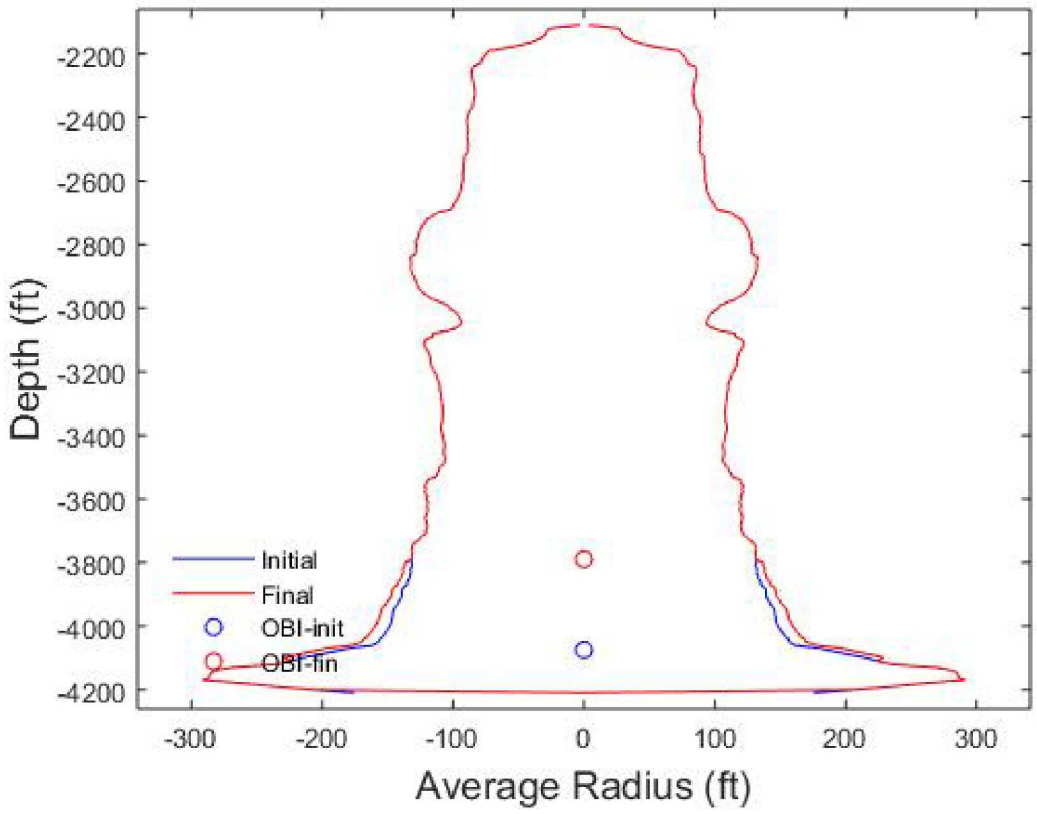

Figure 5-3 Simulated cavern geometry of BC18 with elongated horizontal axis.

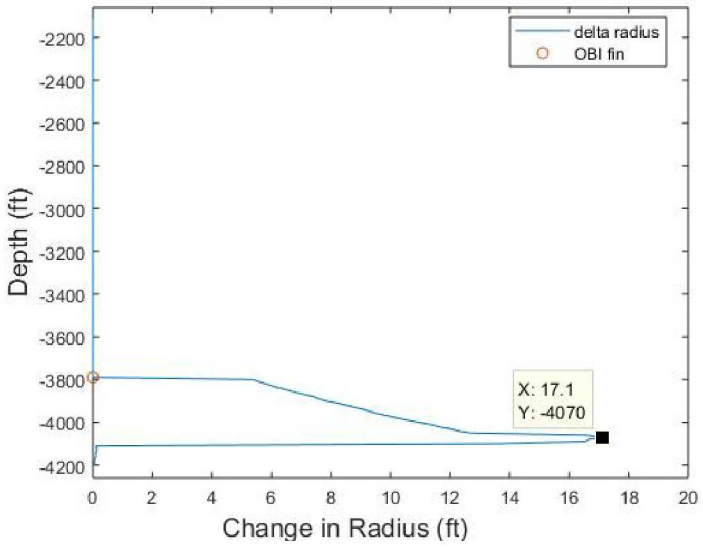

Figure 5-4 Change in radius as a function of depth for BC18.

5.1.2. BC102

BC102 had minor water movement in 2017 (see Table 4-1) which is modeled in one stage summarized in Table 5-4. The average injection rate was 33,966 BBls/day over the 27 days of injection. A standard workover of 60 days was used to finish the first stage. The cumulative injected water volume is shown as a function of time in Figure 5-5. The hanging string was located at 50 ft above the cavern bottom. The initial OBI was 1737 ft above the cavern bottom. The evolution of the OBI over time is shown in Figure 5-6.

Table 5-4 Summary of Simulation Input for BC102

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2640	5230	2590	50	1737	33966	27	60

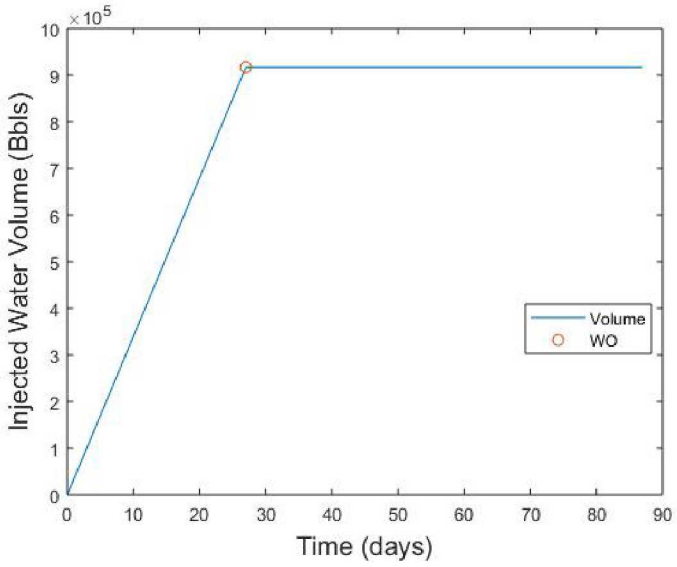

Figure 5-5 Injected water time history for BC102 simulation.

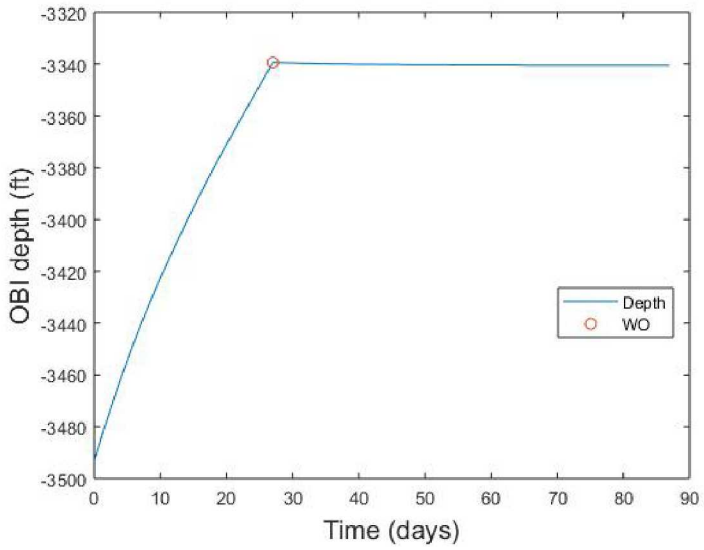

Figure 5-6 OBI depth time history for BC102 simulation.

The outlet specific gravity reached 1.2011, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the workover. As summarized in Table 5-5, the total amount of raw water injected was 0.92 MMB creating a volume of 0.15 MMB by leaching over 1889 ft of the cavern wall out to 2 ft.

Table 5-5 Summary of Simulation Output for BC102

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2002	0.92	0.15	1889	2

The simulated cavern shape as a result of the leaching is shown in Figure 5-7. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2017 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-8.

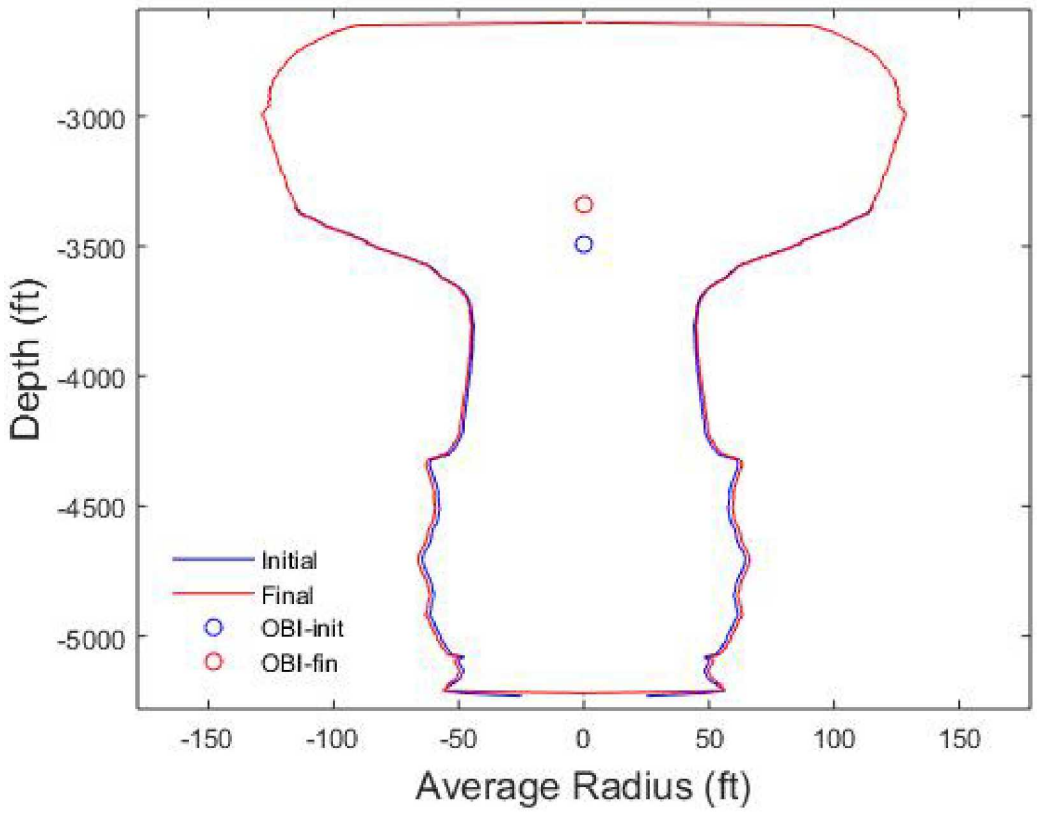

Figure 5-7 Simulated cavern geometry of BC102 with elongated horizontal axis.

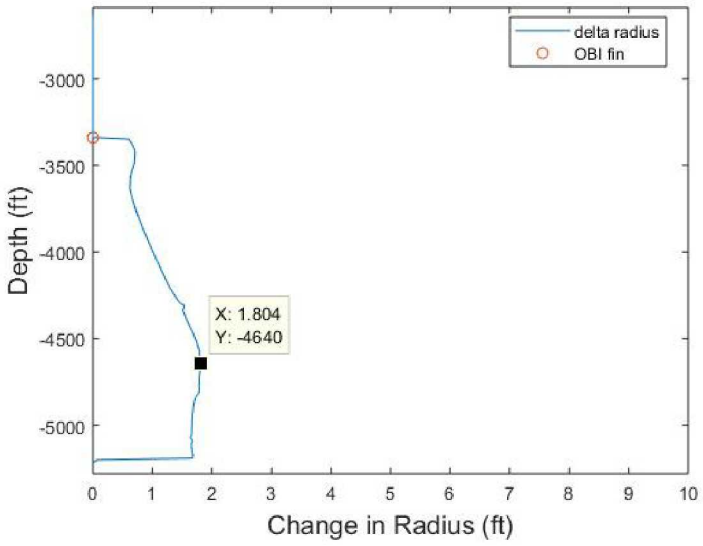

Figure 5-8 Change in radius as a function of depth for BC102.

5.2. Big Hill

Simulation results for Big Hill are summarized in Table 5-6. No caverns at this site have had more than 3MMB of water injected since the last sonar.

Table 5-6 Summary of Simulation Results for Big Hill

Cavern	Latest sonar	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Maximum Change in Radius (ft)
BH101	2012	0.01	0.002	0.3
BH102	2013	1.47	0.25	5
BH104	2012[+]	2.61	0.41	9
BH105	2013	0.02	0.004	0.04
BH106	2015	0.50	0.08	7
BH107	2010	1.63	0.27	18
BH108	2015	1.66	0.27	11
BH109	2015	1.12	0.19	11
BH110	2015	0.24	0.04	4
BH111	2015	0.06	0.01	0
BH114	2013	1.12	0.19	13

[+]Sonar in 2018 following 2017 sales/exchange

5.2.1. BH101

BH101 had minor water movement in 2017 (see Table 4-2) which is modeled in 1 stages summarized in Table 5-7. The average injection rate was 5,257 BBls/day over the 2 days of injection. A standard workover of 60 days was used to finish the first stage. The cumulative injected water volume is shown as a function of time in Figure 5-9**Error! Reference source not found.**. The hanging string was located at 13 ft above the cavern bottom. The initial OBI was 61 ft above the cavern bottom. The evolution of the OBI over time is shown in Figure 5-10.

Table 5-7 Summary of Simulation Input for BH101

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2260	4080	1820	13	61	5257	2	60

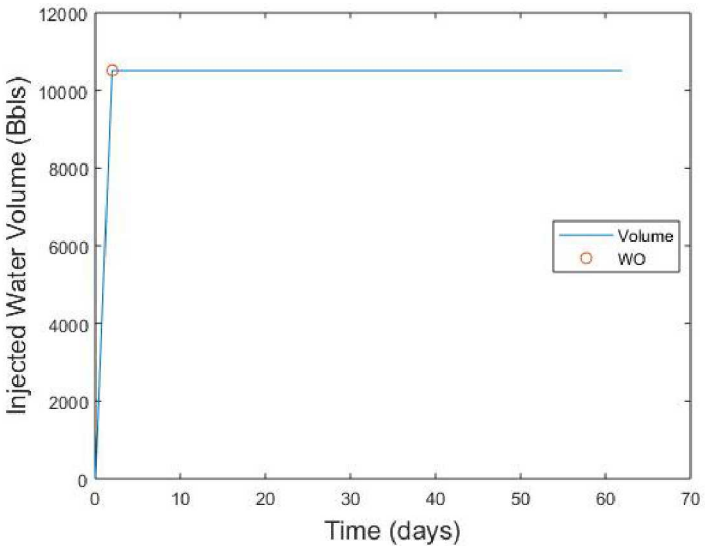

Figure 5-9 Injected water time history for BH101 simulation.

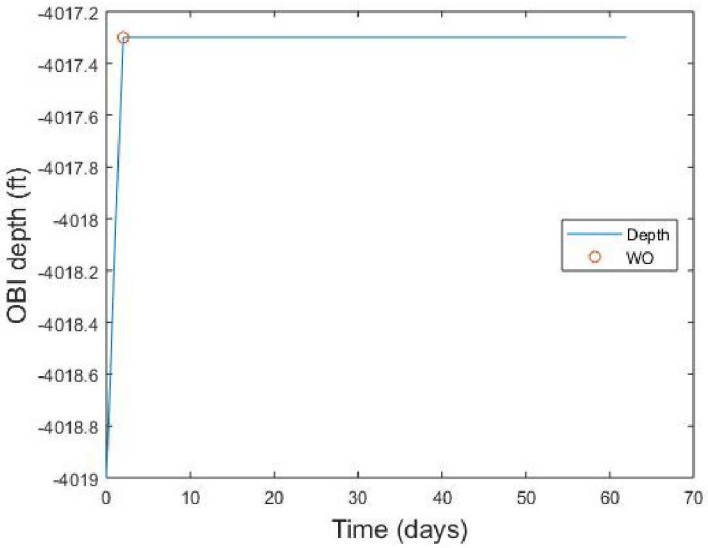

Figure 5-10 OBI depth time history for BH101 simulation.

The outlet specific gravity reached 1.2011, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the workover. As summarized in Table 5-8, the total amount of raw water injected was 0.01 MMB creating a volume of 0.002 MMB by leaching over 63 ft of the cavern wall out to 0.3 ft.

Table 5-8 Summary of Simulation Output for BH101

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2011	0.01	0.002	63	0.3

The simulated cavern shape as a result of the leaching is shown in Figure 5-11. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2012 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-12.

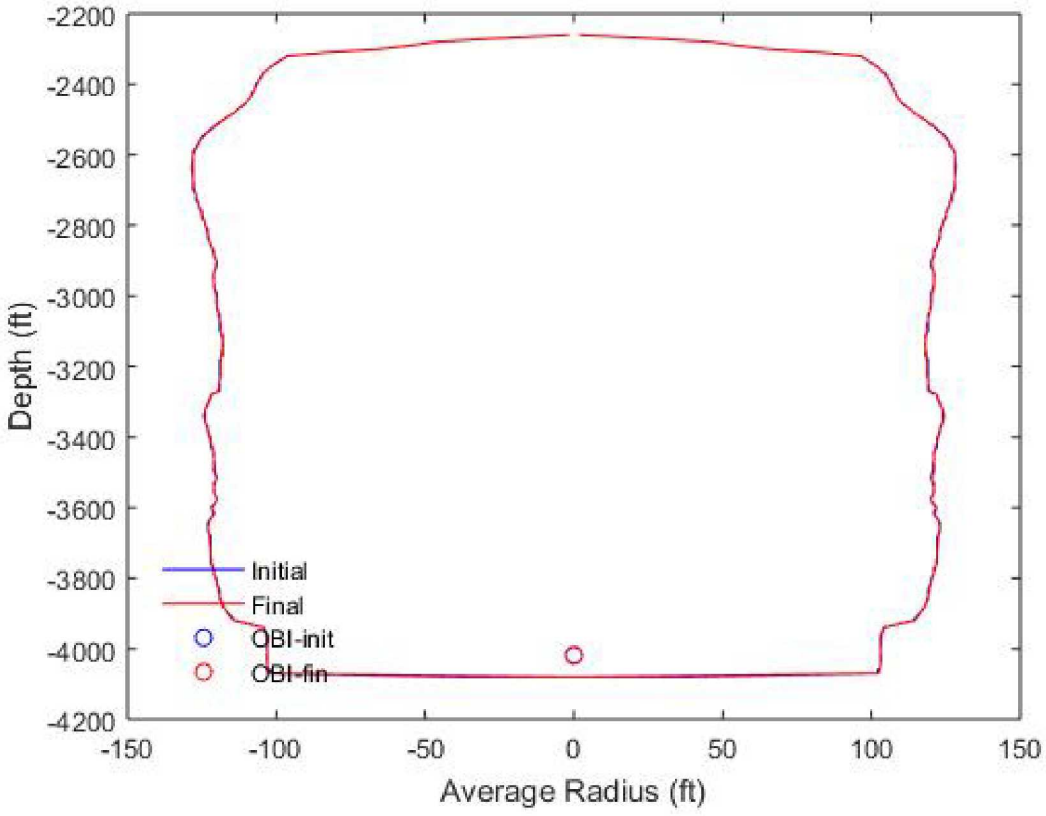

Figure 5-11 Simulated cavern geometry of BH101 with elongated horizontal axis.

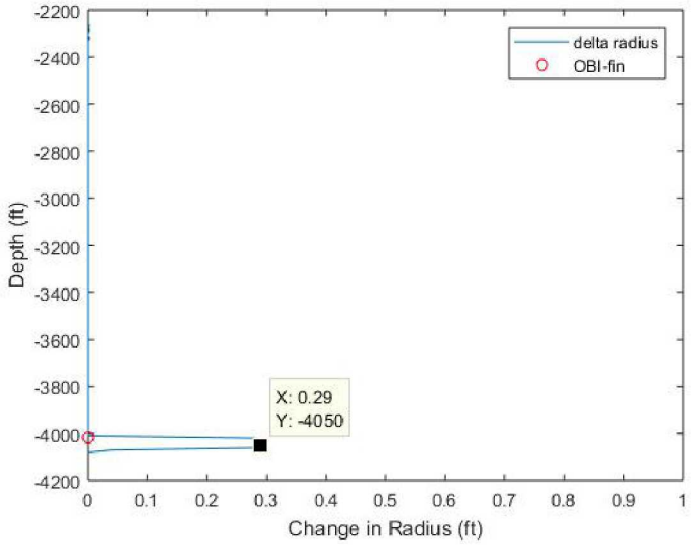

Figure 5-12 Change in radius as a function of depth for BH101.

5.2.2. BH102

BH102 had significant water movement in 2013, 2015, and 2017 (see Table 4-2) which is modeled in 4 separate stages summarized in Table 5-9. The average injection rate for the first stage was 73,354 BBls/day over the 5 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 34,691 BBls/day over the 4 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The average injection rate for the third stage was 12,779 BBls/day over the 72 day injection period. A standard workover duration of 60 days was also used at the end of stage 3. The average injection rate for the fourth stage was 11,943 BBls/day over the 4 day injection period. A standard workover duration of 60 days was also used at the end of stage 4. The cumulative injected water volume is shown as a function of time in Figure 5-13. The hanging string was located at 95 ft above the cavern bottom for stages 1 and 2 and 103 ft above the cavern bottom for stages 3 and 4. The initial OBI was 498 ft above the cavern bottom for stage 1, the output OBI from stage 1 was used as the input OBI for stage 2, 410 ft above the cavern bottom for stage 3, and 567 ft above the cavern bottom for stage 4. The evolution of the OBI over time is shown in Figure 5-14. The sharp change in OBI depth at the end of stage 2 represents a time where the simulated OBI depth at the end of the stage exceeds the measured depth at the beginning of the following stage.

Table 5-9 Summary of Simulation Input for BH102

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2150	4050	1900	95	498	73354	5	60
2	2150	4050	1900	95	---	34691	4	60
3	2150	4050	1900	103	410	12779	72	60
4	2150	4050	1900	103	567	11943	4	60

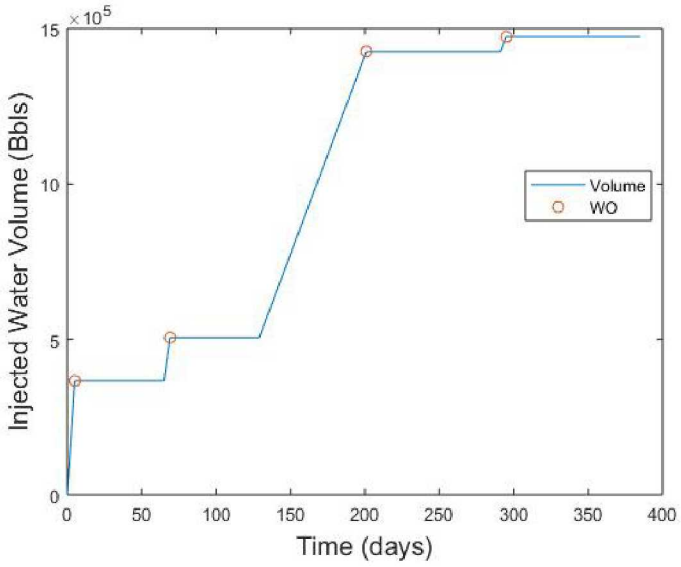

Figure 5-13 Injected water time history for BH102 simulation.

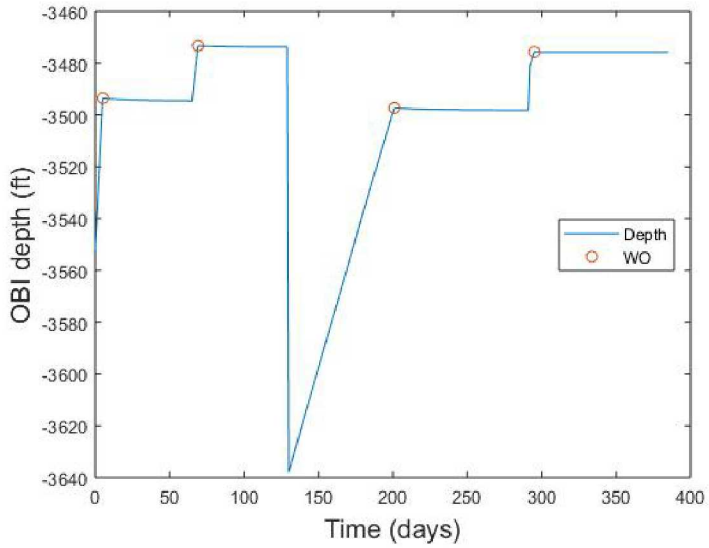

Figure 5-14 OBI depth time history for BH102 simulation.

The outlet specific gravity reached 1.2019, equivalent to the value of 1.2019 expected for salt saturated water, suggesting that leaching completed at the end of the stage 4 workover. As summarized in Table 5-10, the total amount of raw water injected was 1.47 MMB creating a volume of 0.25 MMB by leaching over 570 ft of the cavern wall out to 5 ft.

Table 5-10 Summary of Simulation Output for BH102

Output	Injected	Cavern	Height	Max

Specific Gravity	Water Volume (MMB)	Volume Created (MMB)	Affected (ft)	Change in Radius (ft)
1.2019	1.47	0.25	570	5

The simulated cavern shape as a result of the leaching is shown in Figure 5-15. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2013 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred 100 ft to 400 ft above the bottom of the cavern, as shown in Figure 5-16.

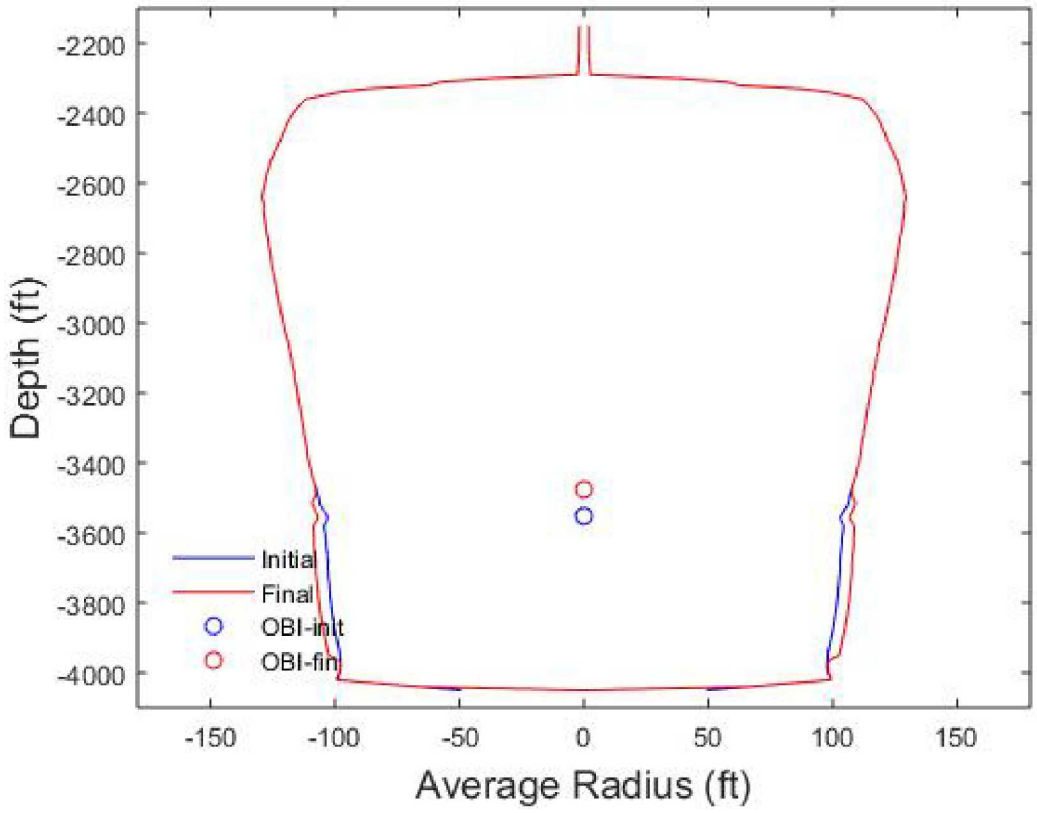

Figure 5-15 Simulated cavern geometry of BH102 with elongated horizontal axis.

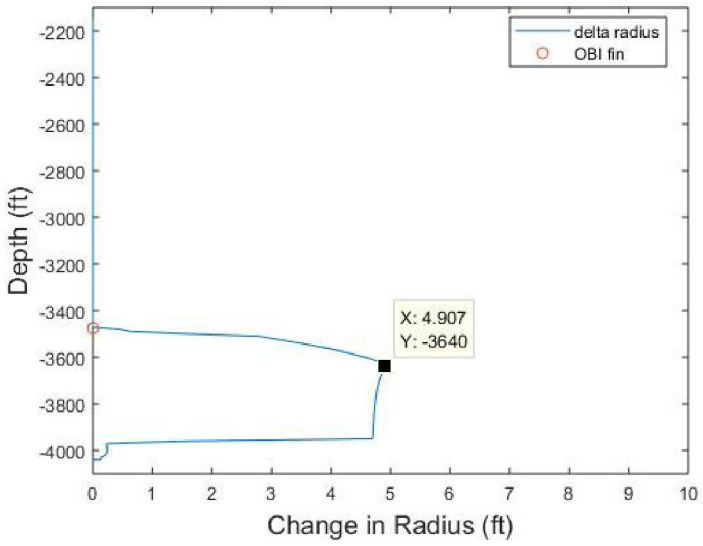

Figure 5-16 Change in radius as a function of depth for BH102.

5.2.3. BH104

BH104 had significant water movement in 2013 and 2017 (see Table 4-2) which is modeled in 4 separate stages summarized in Table 5-11. The average injection rate for the first stage was 82,809 BBls/day over the 17 days of injection. A workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 56,054 BBls/day over the 2 day injection period. A standard workover duration of 60 days was used at the end of stage 2. The average injection rate for the third stage was 14,418 BBls/day over the 71 day injection period. A standard workover duration of 60 days was also used at the end of stage 3. The average injection rate for the fourth stage was 24,639 BBls/day over the 2 day injection period. A standard workover duration of 60 days was also used at the end of stage 4. The cumulative injected water volume is shown as a function of time in Figure 5-17. The hanging string was located at 11 ft above the cavern bottom for stages 1 and 2 and 22 and 24 ft above the cavern bottom for stages 3 and 4, respectively. The initial OBI was 930 ft above the cavern bottom for stage 1, 1132 ft above the cavern bottom for stage 2, 119 ft above the cavern bottom for stage 3, and 263 ft above the cavern bottom for stage 4. The evolution of the OBI over time is shown in Figure 5-18.

Table 5-11 Summary of Simulation Input for BH104

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2120	4200	2080	11	930	82809	17	60
2	2120	4200	2080	11	1132	56054	2	60

3	2120	4200	2080	22	119	14418	71	60
4	2120	4200	2080	24	263	24639	2	60

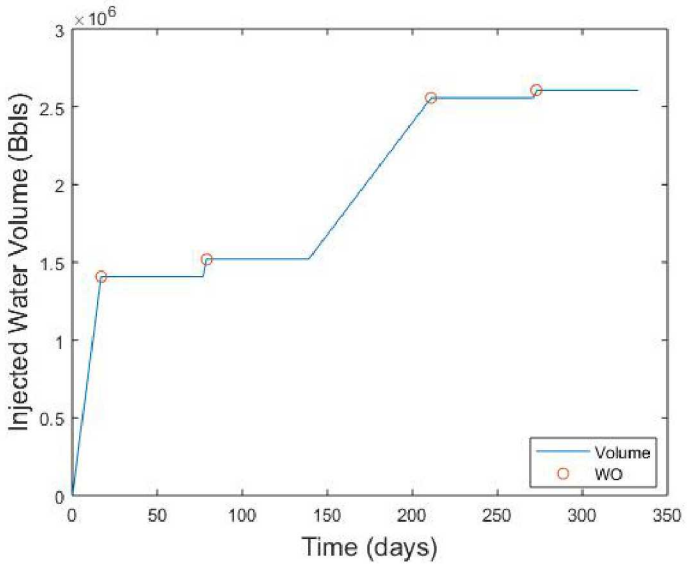

Figure 5-17 Injected water time history for BH104 simulation.

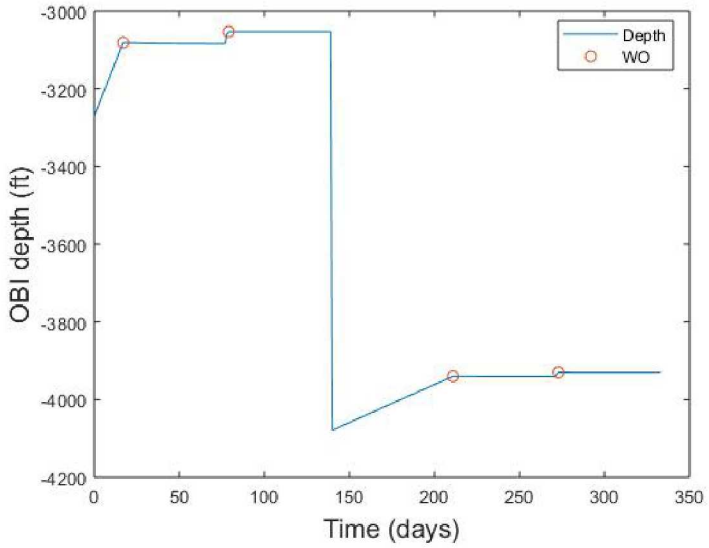

Figure 5-18 OBI depth time history for BH104 simulation.

The outlet specific gravity reached 1.2013, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 4 workover. As summarized in Table 5-12, the total amount of raw water injected was 2.61 MMB creating a volume of 0.26 MMB by leaching over 1150 ft

of the cavern wall out to 9 ft.

Table 5-12 Summary of Simulation Output for BH104

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2013	2.61	0.26	1150	9

The simulated cavern shape as a result of the leaching is shown in Figure 5-19. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2012 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-20.

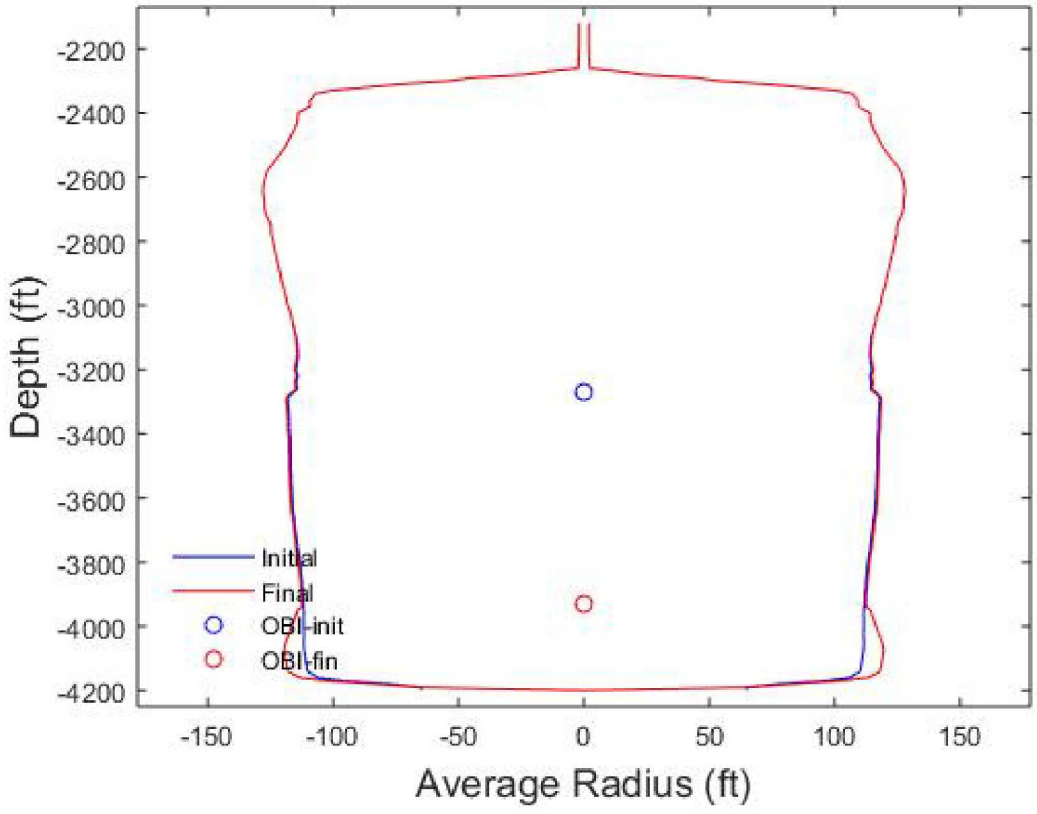

Figure 5-19 Simulated cavern geometry of BH104 with elongated horizontal axis.

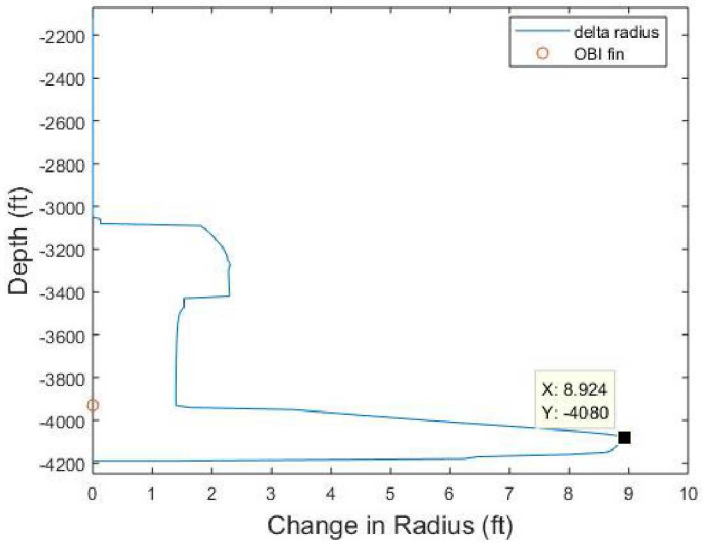

Figure 5-20 Change in radius as a function of depth for BH104.

5.2.4. BH105

BH105 had minor water movement in 2017 (see Table 4-2) which is modeled in 3 separate stages summarized in Table 5-13. This simulation was run with a grid spacing of 2 ft rather than 10 ft over the bottom 1000 ft of the cavern to better resolve the localized leaching at the base of the cavern. The average injection rate for the first stage was 6,567 BBls/day over the 2 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 3,053 BBls/day over the 2 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The average injection rate for the third stage was 1,748 BBls/day over the 2 day injection period. A standard workover duration of 60 days was also used at the end of stage 3. The cumulative injected water volume is shown as a function of time in Figure 5-21. The hanging string was located at 18 ft above the cavern bottom for all three stages. The initial OBI was 770 ft above the cavern bottom for stage 1,and the output OBI for stages 1 and 2 were used as the input OBI for stages 2 and 3, respectively. The evolution of the OBI over time is shown in Figure 5-22.

Table 5-13 Summary of Simulation Input for BH105

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2280	4040	1760	18	770	6567	2	60
2	2280	4040	1760	18	---	3053	2	60
3	2280	4040	1760	18	---	1748	2	60

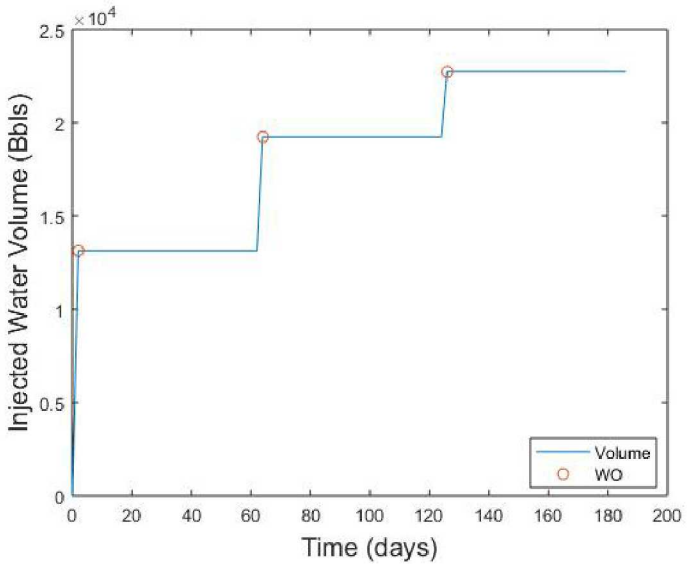

Figure 5-21 Injected water time history for BH105 simulation.

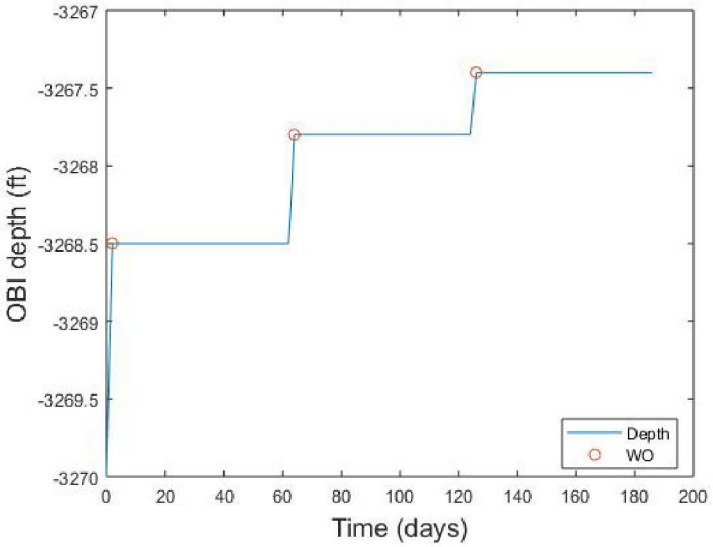

Figure 5-22 OBI depth time history for BH105 simulation.

The outlet specific gravity reached 1.2019, equivalent to the value of 1.2019 expected for salt saturated water, suggesting that leaching completed at the end of the stage 3 workover. As summarized in Table 5-14, the total amount of raw water injected was 0.02 MMB creating a volume of 0.00 MMB by leaching over 743 ft of the cavern wall out to 0 ft.

Table 5-14 Summary of Simulation Output for BH105

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2019	0.02	0.004	773	0.04

The simulated cavern shape as a result of the leaching is shown in Figure 5-23. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2013 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-24.

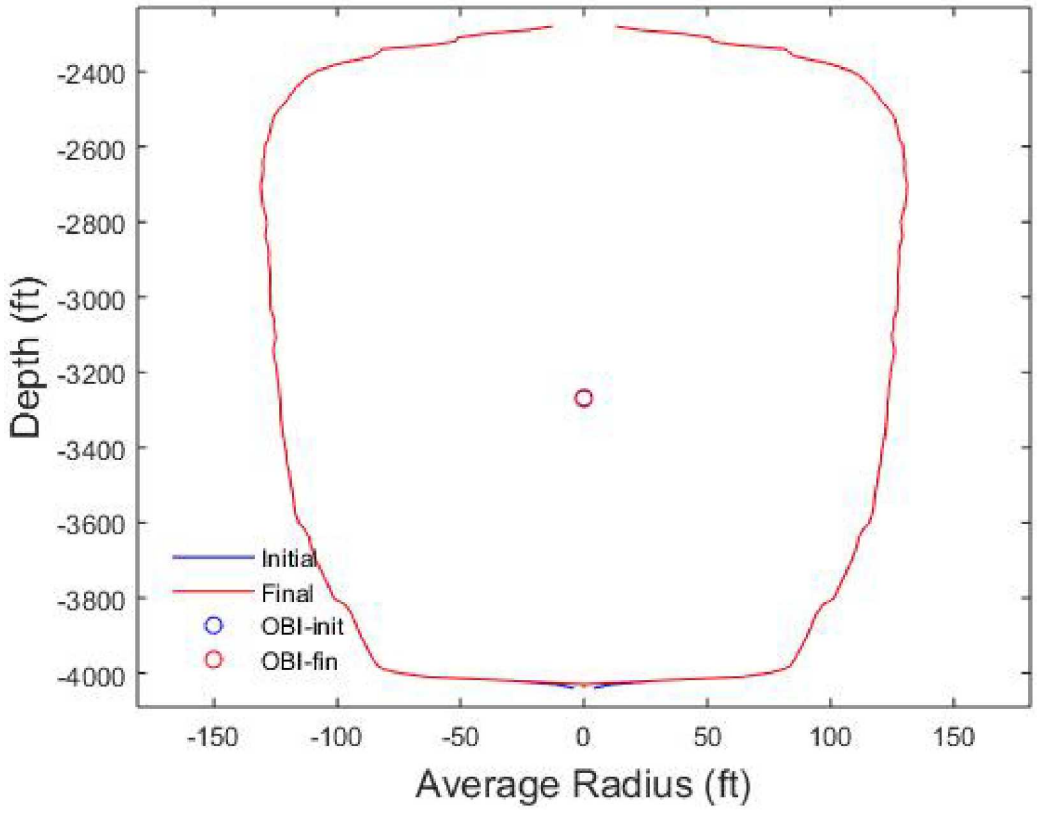

Figure 5-23 Simulated cavern geometry of BH105 with elongated horizontal axis.

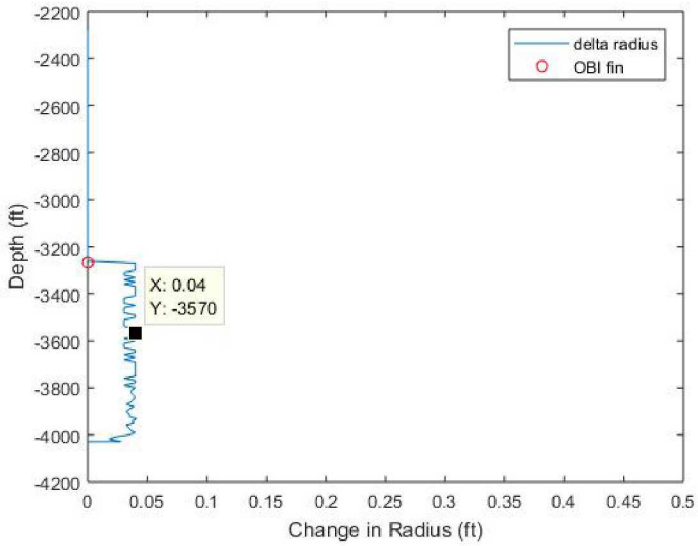

Figure 5-24 Change in radius as a function of depth for BH105.

5.2.5. BH106

BH106 had minor water movement in 2017 (see Table 4-2) which is modeled in a single stage summarized in Table 5-15. The average injection rate was 17,197 BBls/day over the 29 days of injection. A standard workover of 60 days was used to finish the stage. The cumulative injected water volume is shown as a function of time in Figure 5-25. The hanging string was located at 20 ft above the cavern bottom. The initial OBI was 43 ft above the cavern bottom. The evolution of the OBI over time is shown in Figure 5-26.

Table 5-15 Summary of Simulation Input for BH106

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2280	4080	1800	20	43	17197	29	60

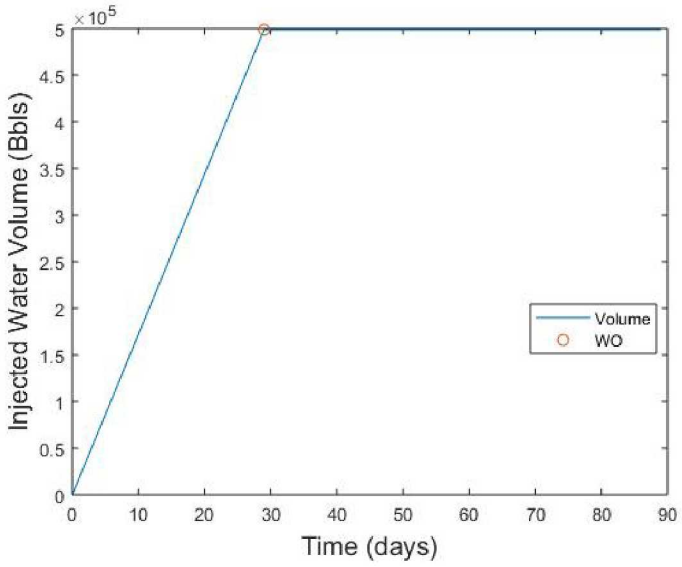

Figure 5-25 Injected water time history for BH106 simulation.

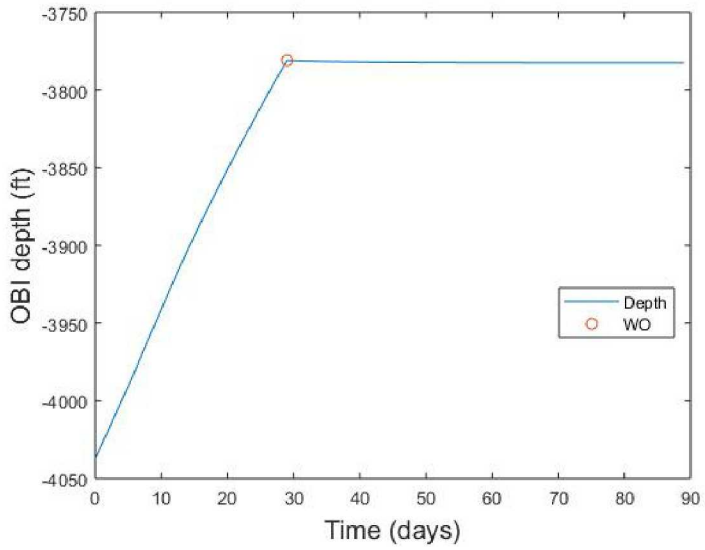

Figure 5-26 OBI depth time history for BH106 simulation.

The outlet specific gravity reached 1.2010, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the workover. As summarized in Table 5-16, the total amount of raw water injected was 0.50 MMB creating a volume of 0.08 MMB by leaching over 287 ft of the cavern wall out to 7 ft.

Table 5-16 Summary of Simulation Output for BH106

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2010	0.50	0.08	287	7

The simulated cavern shape as a result of the leaching is shown in Figure 5-27. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2015 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-28.

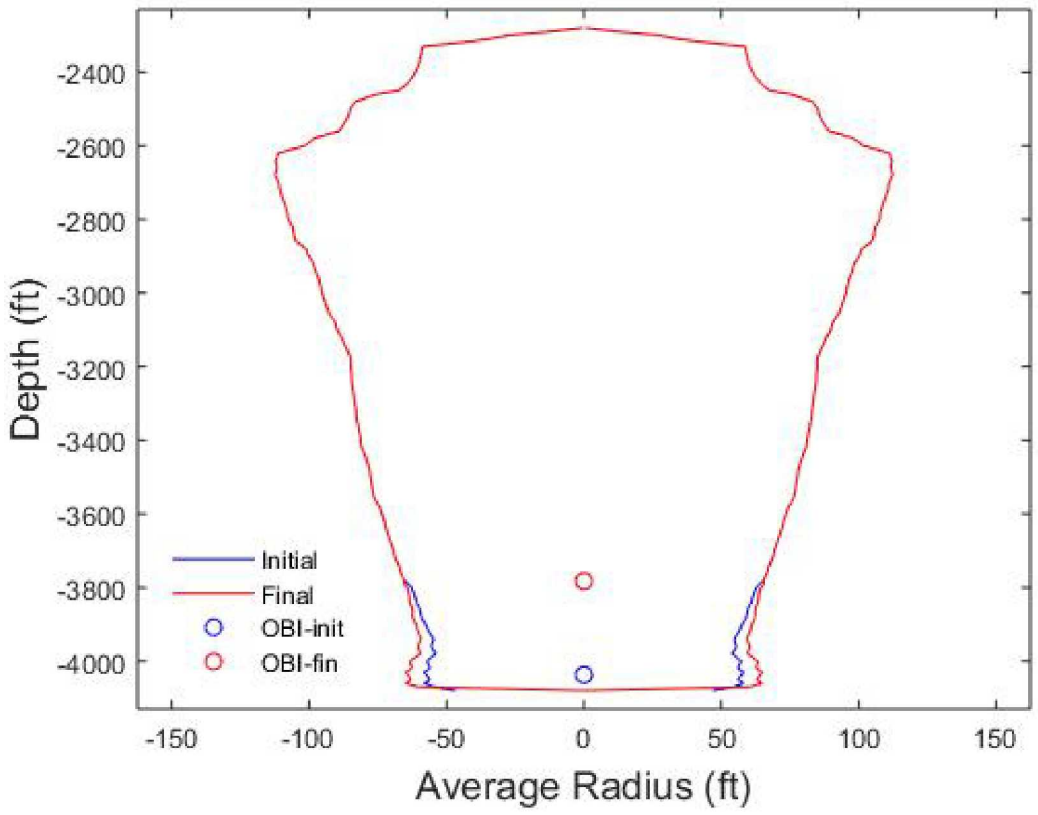

Figure 5-27 Simulated cavern geometry of BH106 with elongated horizontal axis.

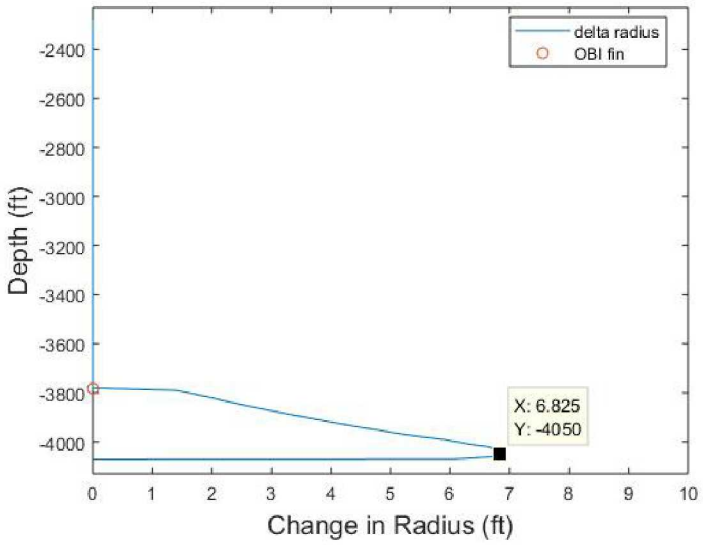

Figure 5-28 Change in radius as a function of depth for BH106.

5.2.6. BH107

BH107 had significant water movement in 2015 and 2017 (see Table 4-2) which is modeled in 3 separate stages summarized in Table 5-17. The average injection rate for the first stage was 34,662 BBls/day over the 2 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 19,197 BBls/day over the 41 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The average injection rate for the third stage was 23,397 BBls/day over the 34 day injection period. A standard workover duration of 60 days was also used at the end of stage 3. The cumulative injected water volume is shown as a function of time in Figure 5-29. The hanging string was located at 23 ft above the cavern bottom for all three stages. The initial OBI was 33 ft above the cavern bottom for stage 1, 39 ft above the cavern bottom for stage 2, and 266 ft above the cavern bottom for stage 3. The evolution of the OBI over time is shown in Figure 5-30. The sharp change in OBI depth at the end of stage 1 represents a time where the simulated OBI depth at the end of the stage exceeds the measured depth at the beginning of the following stage.

Table 5-17 Summary of Simulation Input for BH107

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2120	4090	1970	23	33	34662	2	60
2	2120	4090	1970	23	39	19197	41	60
3	2120	4090	1970	23	266	23397	34	60

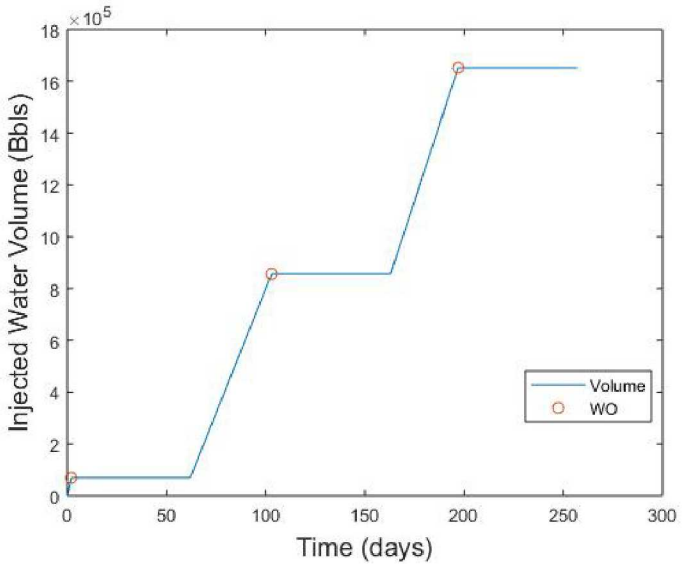

Figure 5-29 Injected water time history for BH107 simulation.

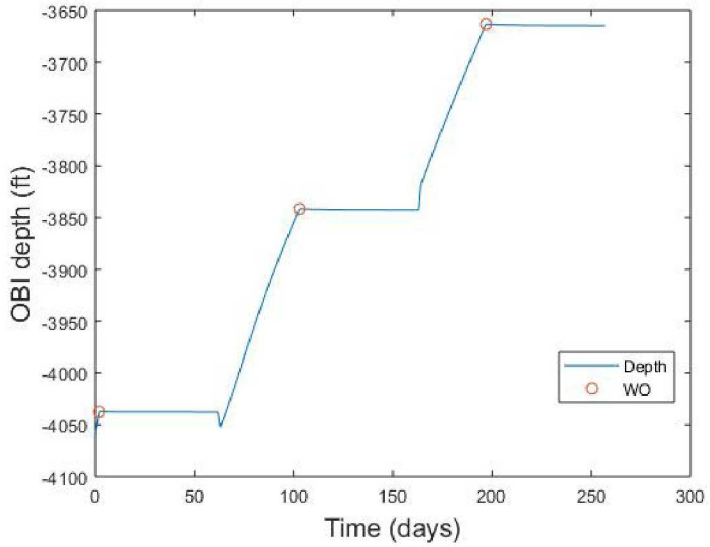

Figure 5-30 OBI depth time history for BH107 simulation.

The outlet specific gravity reached 1.1991, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 3 workover. As summarized in Table 5-18, the total amount of raw water injected was 1.63 MMB creating a volume of 0.27 MMB by leaching over 415 ft of the cavern wall out to 18 ft.

Table 5-18 Summary of Simulation Output for BH107

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1991	1.63	0.27	415	18

The simulated cavern shape as a result of the leaching is shown in Figure 5-31. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2010 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-32. The three stage leach without a change in the hanging string depth resulted in a widening of the cavern floor.

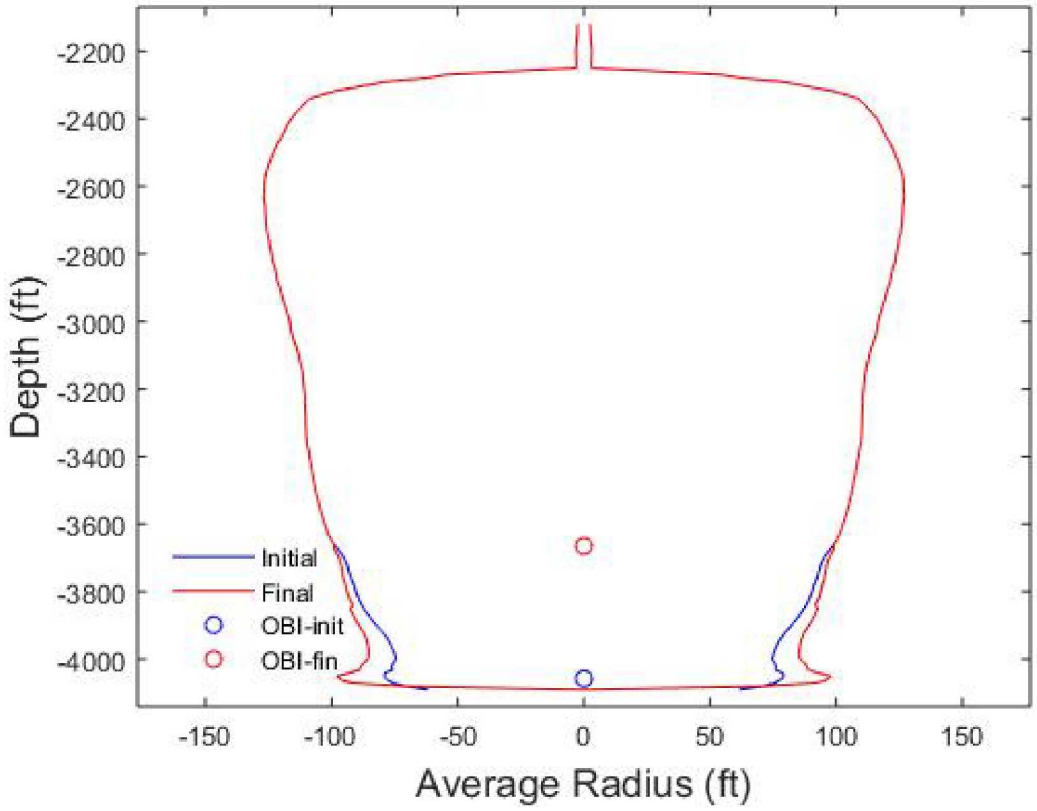

Figure 5-31 Simulated cavern geometry of BH107 with elongated horizontal axis.

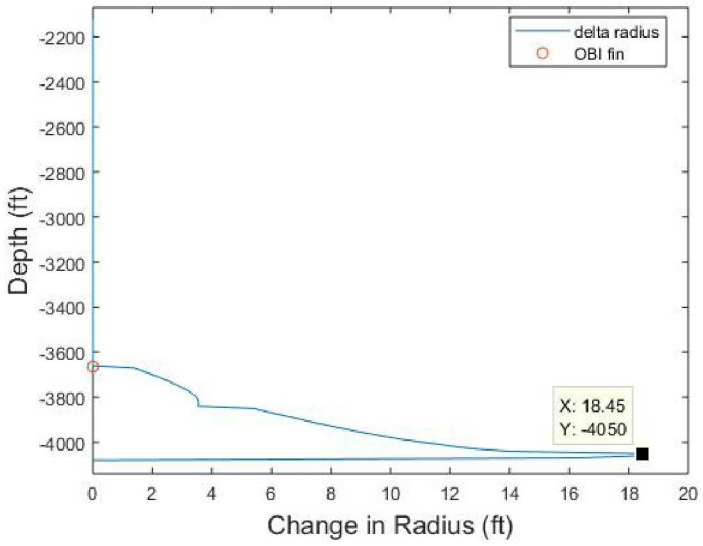

Figure 5-32 Change in radius as a function of depth for BH107.

5.2.7. BH108

BH108 had moderate water movement in 2017 (see Table 4-2) which is modeled in 2 separate stages summarized in Table 5-19. The average injection rate for the first stage was 18,095 BBls/day over the 34 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 38,629 BBls/day over the 27 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The cumulative injected water volume is shown as a function of time in Figure 5-33. The hanging string was located at 11 ft and 6 ft above the cavern bottom for stages 1 and 2, respectively. The initial OBI was 50 ft above the cavern bottom for stage 1 and 259 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-34.

Table 5-19 Summary of Simulation Input for BH108

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2150	4120	1970	11	50	18095	34	60
2	2150	4120	1970	6	259	38629	27	60

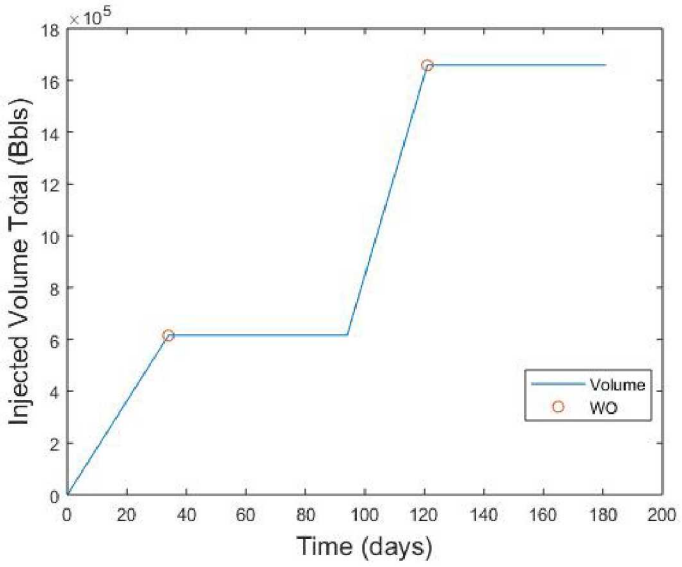

Figure 5-33 Injected water time history for BH108 simulation.

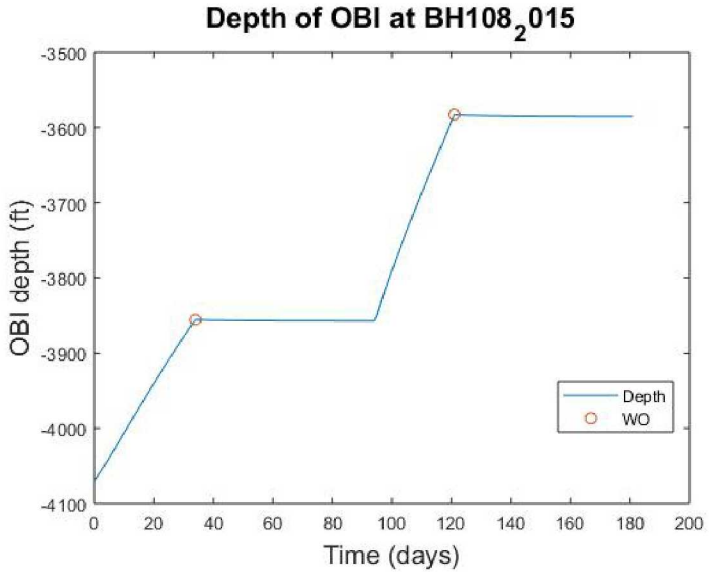

Figure 5-34 OBI depth time history for BH108 simulation.

The outlet specific gravity reached 1.1996, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-20, the total amount of raw water injected was 1.66 MMB creating a volume of 0.27 MMB by leaching over 525 ft of the cavern wall out to 11 ft.

Table 5-20 Summary of Simulation Output for BH108

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1996	1.66	0.27	525	11

The simulated cavern shape as a result of the leaching is shown in Figure 5-35. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2015 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-36.

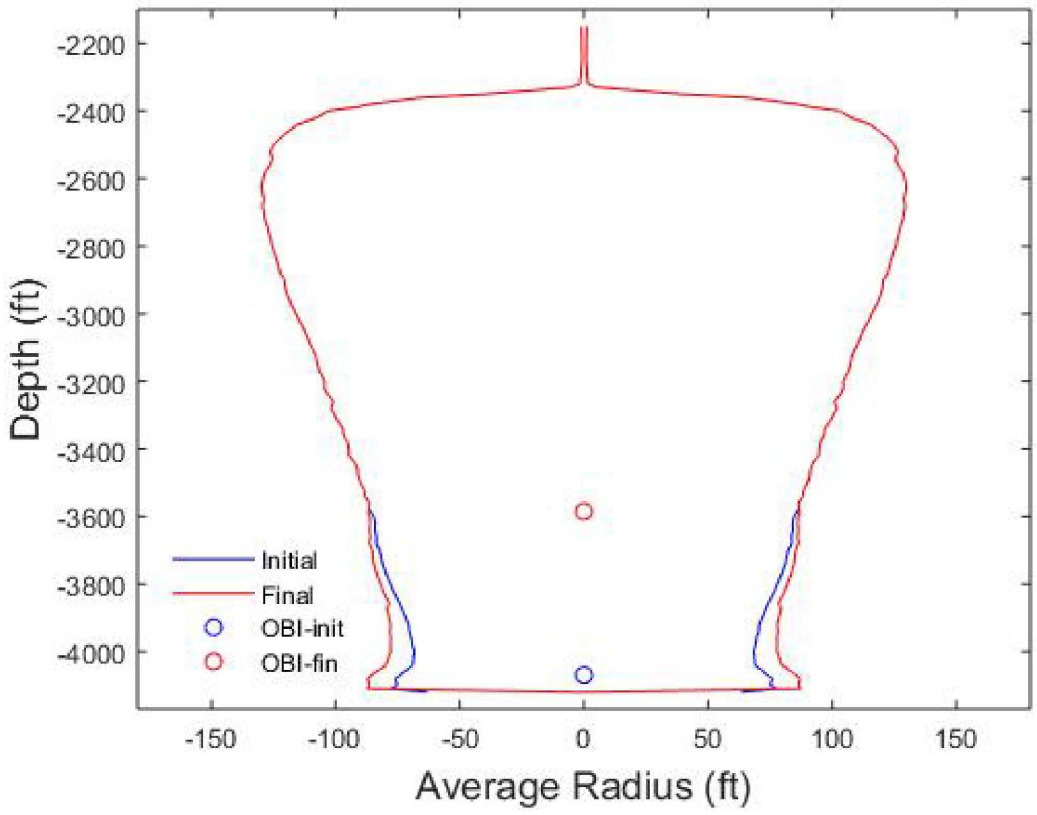

Figure 5-35 Simulated cavern geometry of BH108 with elongated horizontal axis.

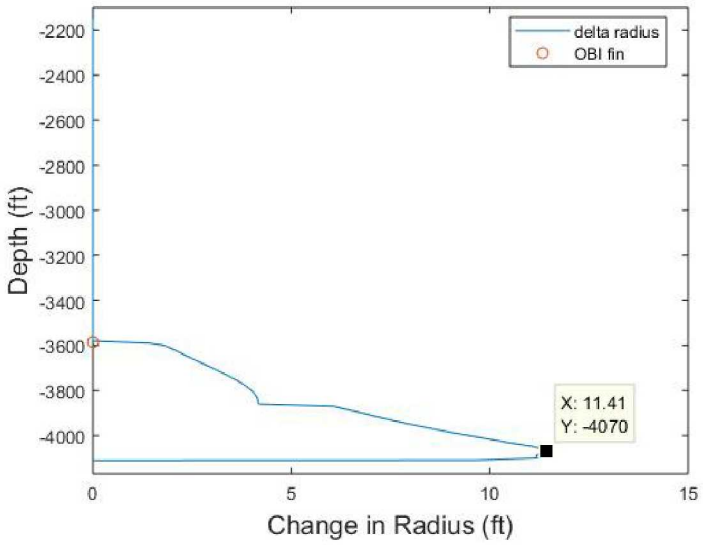

Figure 5-36 Change in radius as a function of depth for BH108.

5.2.8. BH109

BH109 had moderate water movement in 2017 (see Table 4-2) which is modeled in 2 separate stages summarized in Table 5-21. The average injection rate for the first stage was 7,587 BBls/day over the 93 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 15,236 BBls/day over the 27 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The cumulative injected water volume is shown as a function of time in Figure 5-37. The hanging string was located at 19 ft above the cavern bottom for both stages. The initial OBI was 56 ft above the cavern bottom for stage 1 and 284 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-38. The sharp change in OBI depth at the end of stage 1 represents a time where the simulated OBI depth at the end of the stage exceeds the measured depth at the beginning of the following stage.

Table 5-21 Summary of Simulation Input for BH109

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2120	4220	2100	19	56	7587	93	60
2	2120	4220	2100	19	284	15236	27	60

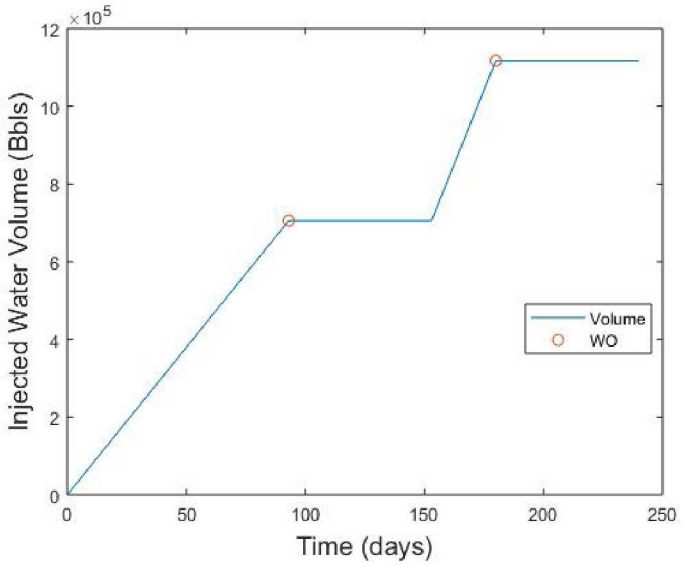

Figure 5-37 Injected water time history for BH109 simulation.

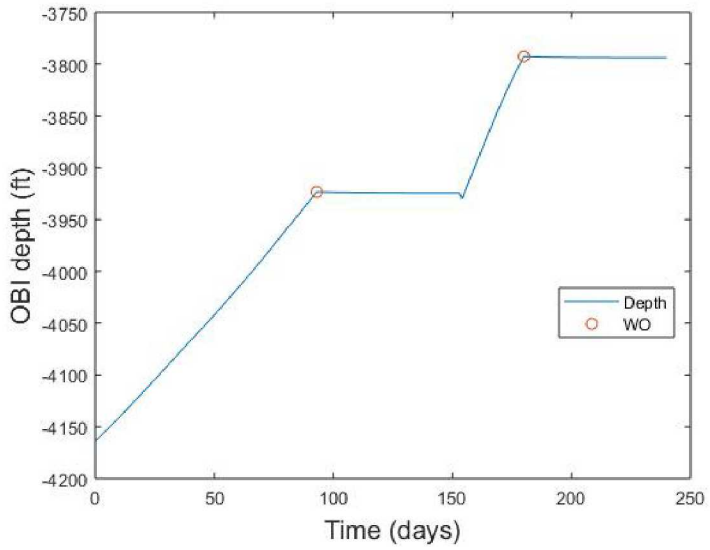

Figure 5-38 OBI depth time history for BH109 simulation.

The outlet specific gravity reached 1.2006, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-22, the total amount of raw water injected was 1.12 MMB creating a volume of 0.19 MMB by leaching over 416 ft of the cavern wall out to 11 ft.

Table 5-22 Summary of Simulation Output for BH109

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2006	1.12	0.19	416	11

The simulated cavern shape as a result of the leaching is shown in Figure 5-39. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2015 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-40.

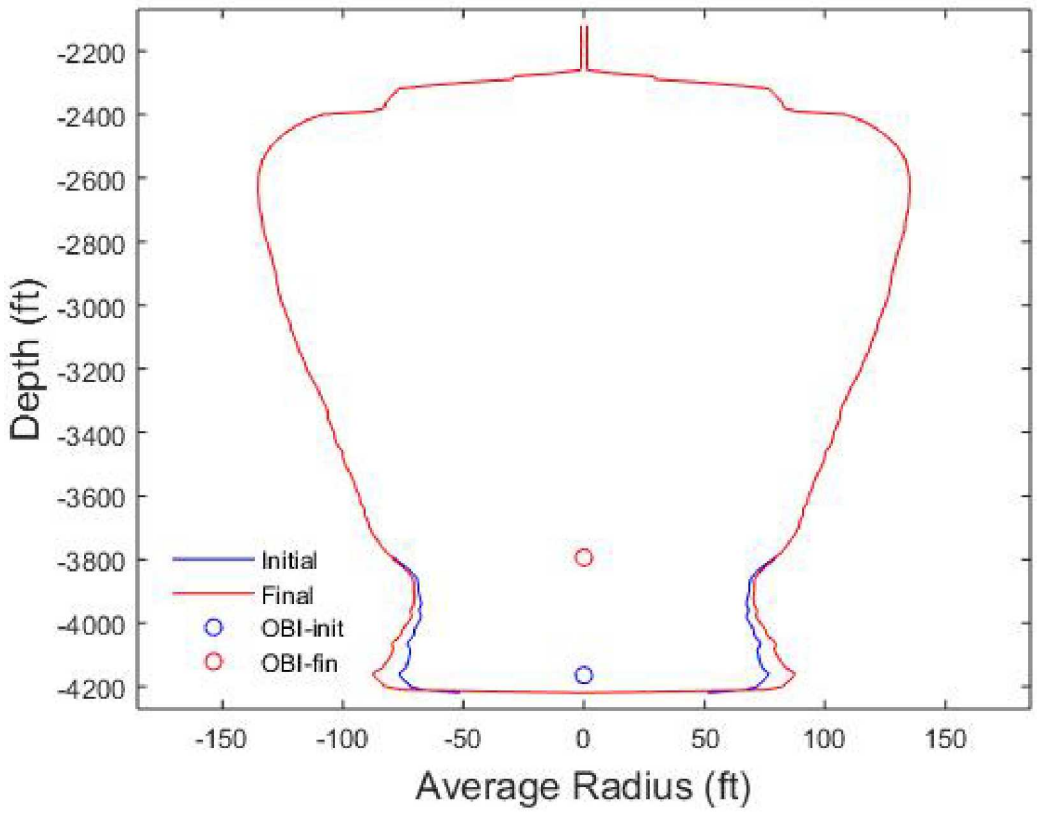

Figure 5-39 Simulated cavern geometry of BH109 with elongated horizontal axis.

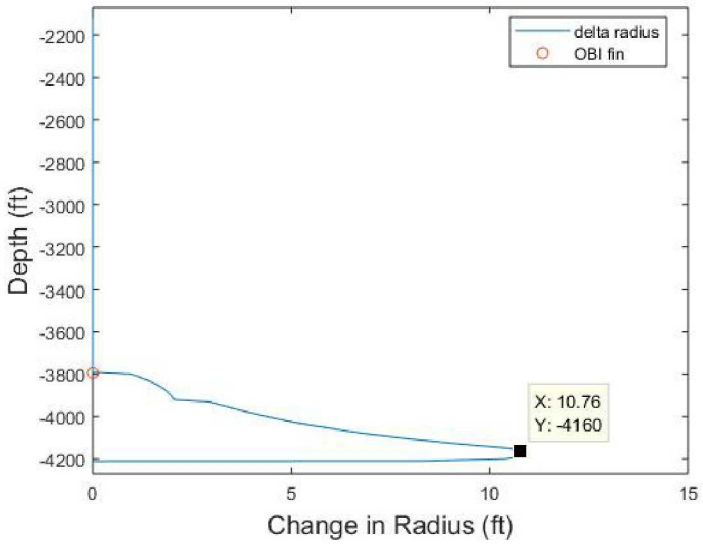

Figure 5-40 Change in radius as a function of depth for BH109.

5.2.9. BH110

BH110 had minor water movement in 2017 (see Table 4-2) which is modeled in 2 separate stages summarized in Table 5-23. The average injection rate for the first stage was 10,273 BBls/day over the 34 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 22,977 BBls/day over the 19 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The cumulative injected water volume is shown as a function of time in Figure 5-41. The hanging string was located at 34 ft above the cavern bottom for stage 1 and 19 ft above the cavern bottom for stage 2. The initial OBI was 93 ft above the cavern bottom for stage 1 and 124 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-42. The sharp change in OBI depth at the end of stage 1 represents a time where the simulated OBI depth at the end of the stage exceeds the measured depth at the beginning of the following stage.

Table 5-23 Summary of Simulation Input for BH110

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2120	4200	2080	34	93	10273	34	60
2	2120	4200	2080	19	124	22977	19	60

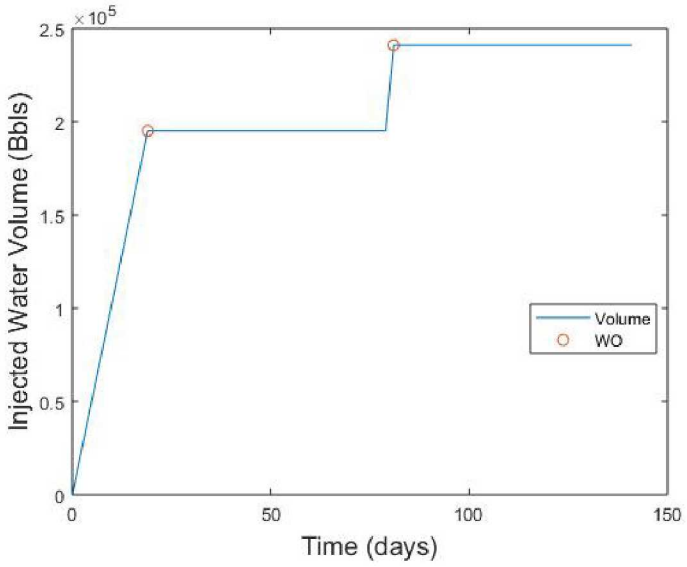

Figure 5-41 Injected water time history for BH110 simulation.

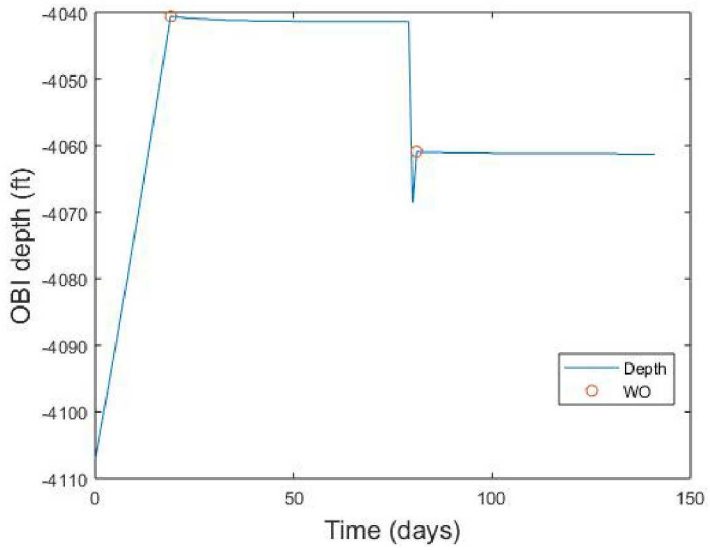

Figure 5-42 OBI depth time history for BH110 simulation.

The outlet specific gravity reached 1.2009, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-24, the total amount of raw water injected was 0.24 MMB creating a volume of 0.04 MMB by leaching over 129 ft of the cavern wall out to 4 ft.

Table 5-24 Summary of Simulation Output for BH110

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2009	0.24	0.04	129	4

The simulated cavern shape as a result of the leaching is shown in Figure 5-43. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2015 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-44.

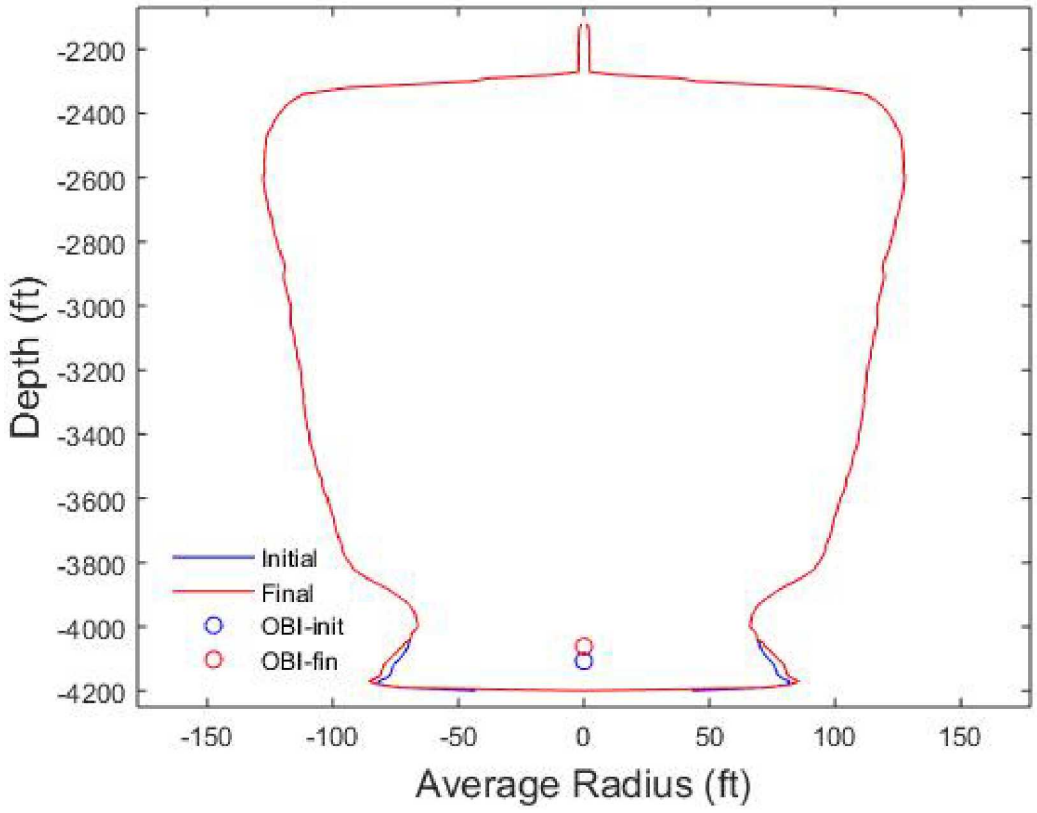

Figure 5-43 Simulated cavern geometry of BH110 with elongated horizontal axis.

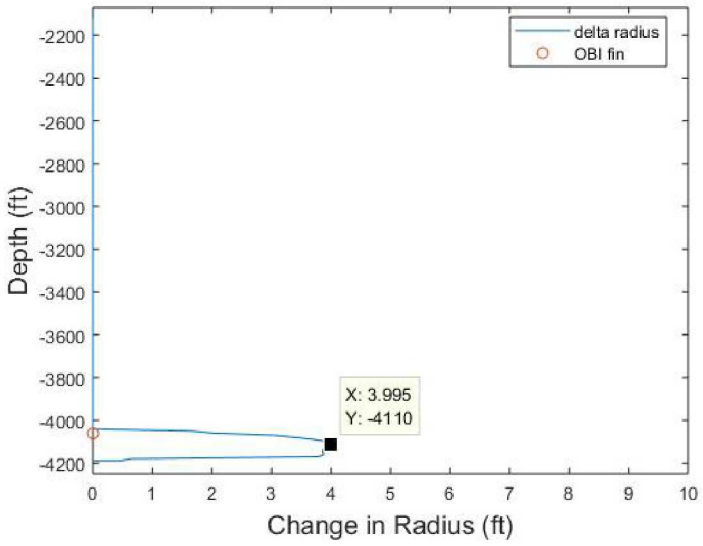

Figure 5-44 Change in radius as a function of depth for BH110.

5.2.10. BH111

BH111 had minor water movement in 2017 (see Table 4-2) which is modeled in 2 separate stages summarized in Table 5-25. The average injection rate for the first stage was 6,882 BBls/day over the 8 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 1,073 BBls/day over the 4 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The cumulative injected water volume is shown as a function of time in Figure 5-45. The hanging string was located at 20 ft and 22 ft above the cavern bottom for stage 1 and stage 2, respectively. The initial OBI was 328 ft above the cavern bottom for stage 1 and 348 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-46.

Table 5-25 Summary of Simulation Input for BH111

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2120	4230	2110	20	328	6882	8	60
2	2120	4230	2110	22	348	1073	4	60

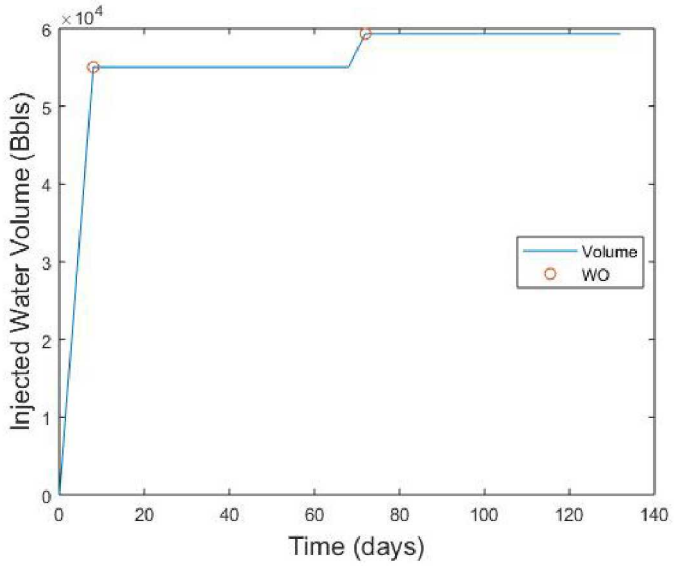

Figure 5-45 Injected water time history for BH111 simulation.

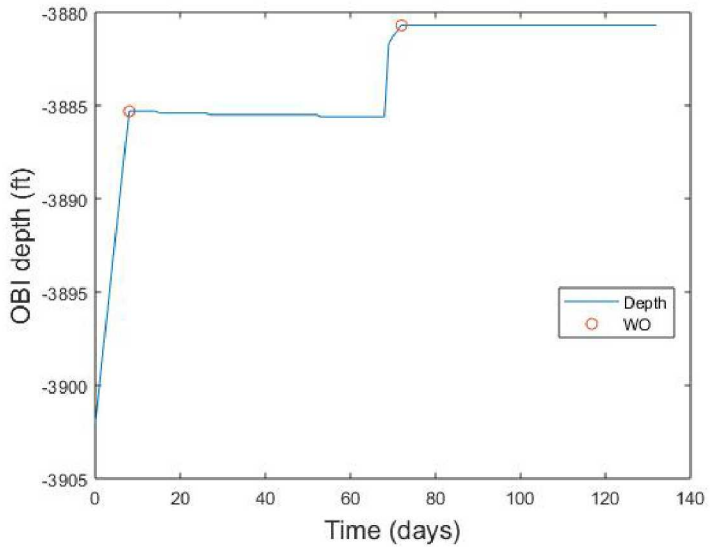

Figure 5-46 OBI depth time history for BH111 simulation.

The outlet specific gravity reached 1.2019, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-26, the total amount of raw water injected was 0.06 MMB creating a volume of 0.01 MMB by leaching over 339 ft of the cavern wall out to 0 ft.

Table 5-26 Summary of Simulation Output for BH111

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2019	0.06	0.01	339	0

The simulated cavern shape as a result of the leaching is shown in Figure 5-47. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2015 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-48.

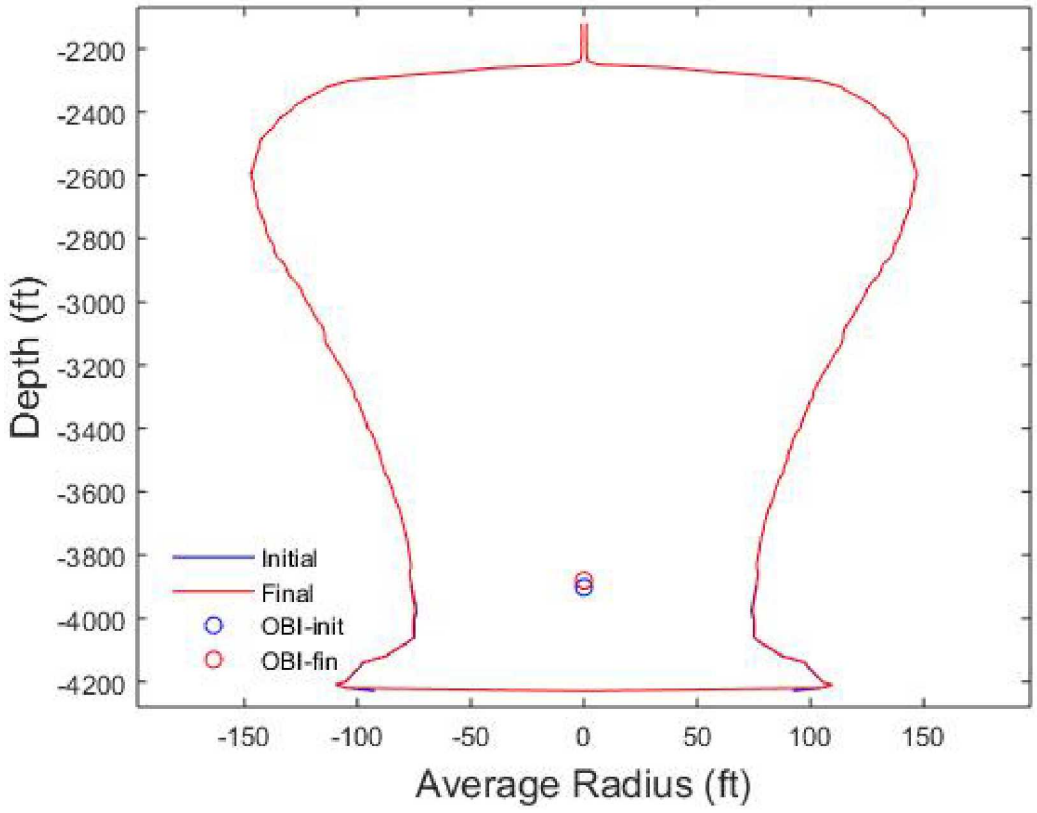

Figure 5-47 Simulated cavern geometry of BH111 with elongated horizontal axis.

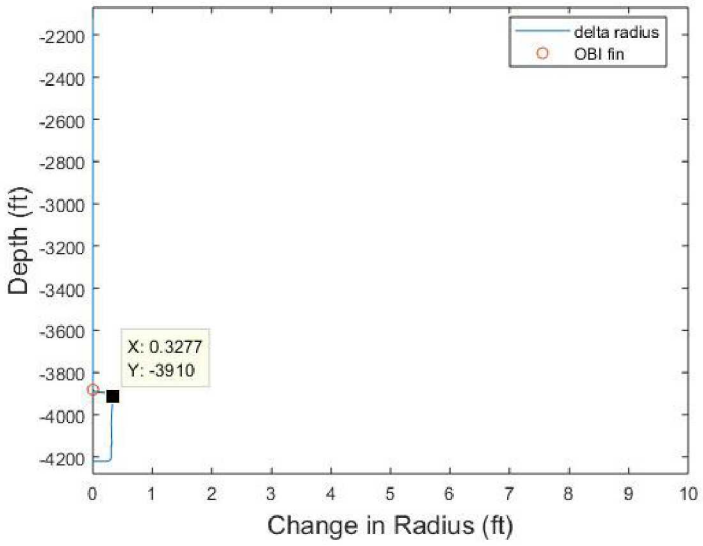

Figure 5-48 Change in radius as a function of depth for BH111.

5.2.11. BH114

BH114 had moderate water movement in 2016 and 2017 (see Table 4-2) which is modeled in 3 separate stages summarized in Table 5-27. The average injection rate for the first stage was 45,281 BBls/day over the 4 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 12,398 BBls/day over the 60 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The average injection rate for the third stage was 24,500 BBls/day over the 2 day injection period. A standard workover duration of 60 days was also used at the end of stage 3. The cumulative injected water volume is shown as a function of time in Figure 5-49. The hanging string was located at 12 ft above the cavern bottom for all three stages. The initial OBI was 36 ft above the cavern bottom for stages 1 and 2 and 316 ft above the cavern bottom for stage 3. The evolution of the OBI over time is shown in Figure 5-50.

Table 5-27 Summary of Simulation Input for BH114

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2140	4130	1990	12	36	45281	4	60
2	2140	4130	1990	12	36	12398	72	60
3	2140	4130	1990	12	316	24500	2	60

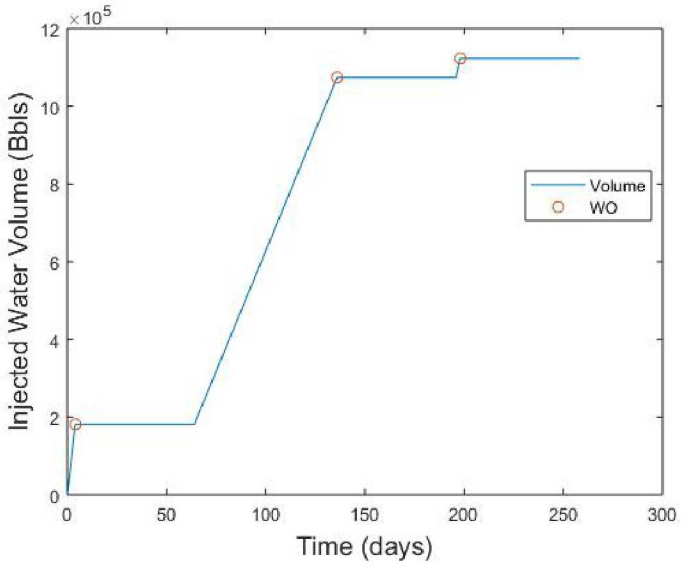

Figure 5-49 Injected water time history for BH114 simulation.

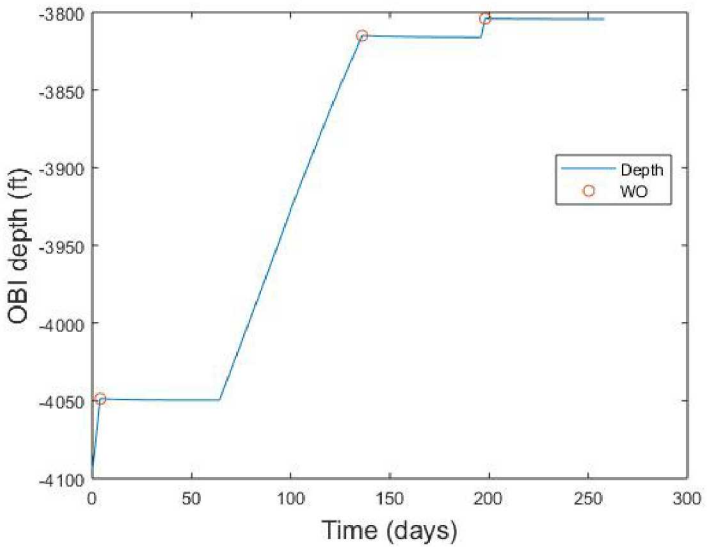

Figure 5-50 OBI depth time history for BH114 simulation.

The outlet specific gravity reached 1.2013, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 3 workover. As summarized in Table 5-28, the total amount of raw water injected was 1.12 MMB creating a volume of 0.19 MMB by leaching over 306 ft of the cavern wall out to 13 ft.

Table 5-28 Summary of Simulation Output for BH114

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2013	1.12	0.19	306	13

The simulated cavern shape as a result of the leaching is shown in Figure 5-51. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2013 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-52.

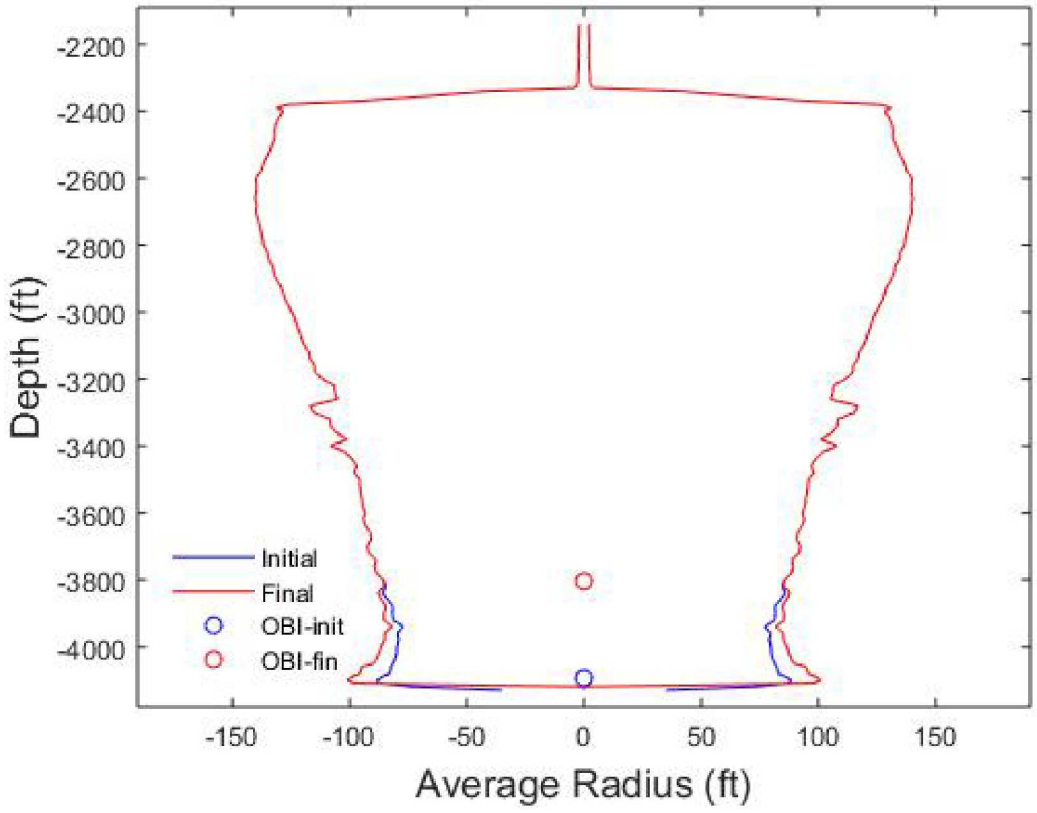

Figure 5-51 Simulated cavern geometry of BH114 with elongated horizontal axis.

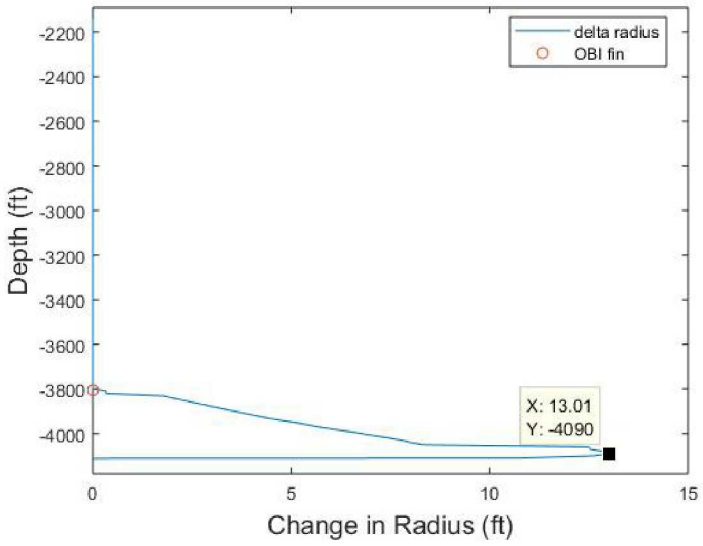

Figure 5-52 Change in radius as a function of depth for BH114.

5.3. Bryan Mound

Simulation results for Bryan Mound are summarized in Table 5-29. Two caverns, BM103 and BM111, have had more than 3MMB of water injected since the last sonar.

Table 5-29 Summary of Simulation Results for Bryan Mound.

Cavern	Latest sonar	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Maximum Change in Radius (ft)
BM005	1987	0.12	0.02	3
BM102	2013	0.41	0.07	3
BM103	2016	3.14	0.52	16
BM108	2016	2.70	0.44	15
BM111	2016[+]	3.28	0.54	16
BM113	2012	0.25	0.04	1
BM114	2012	1.16	0.19	3
BM115	2011	0.43	0.07	7
BM116	2011	1.60	0.26	4

[+]Sonar in 2018 following 2017 sales/exchange
Shading denotes caverns with more than 3 MMB of injected raw water

5.3.1. BM005

BM005 had minor water movement in 2017 (see Table 4-3) which is modeled in 1 stage summarized in Table 5-30. This simulation was run with a grid spacing of 3 ft

rather than 10 ft to better resolve the localized leaching at the base of the cavern. The average injection rate was 1,601 BBls/day over the 77 days of injection. An extended workover of 360 days was needed for the outlet specific gravity to approach 1.2013 in this large cavern. The cumulative injected water volume is shown as a function of time in Figure 5-53. The hanging string was located at 20 ft above the cavern bottom. The initial OBI was 36 ft above the cavern bottom. The evolution of the OBI over time is shown in Figure 5-54.

Table 5-30 Summary of Simulation Input for BM005

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2140	3220	1080	20	36	1601	77	360

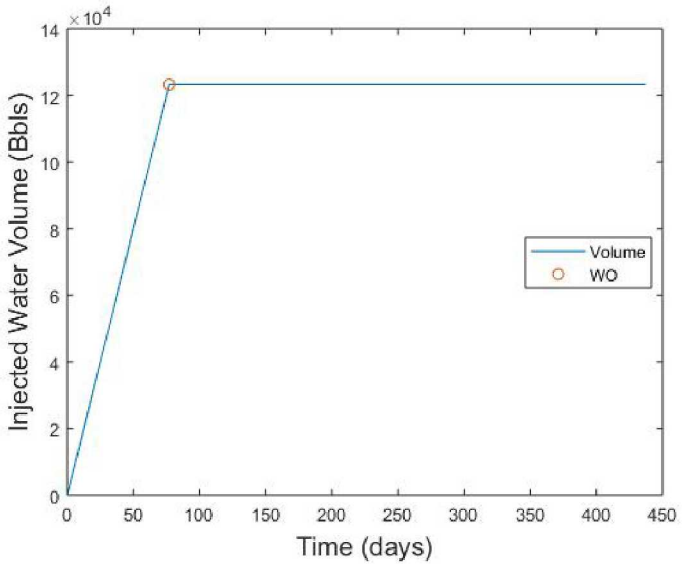

Figure 5-53 Injected water time history for BM005 simulation.

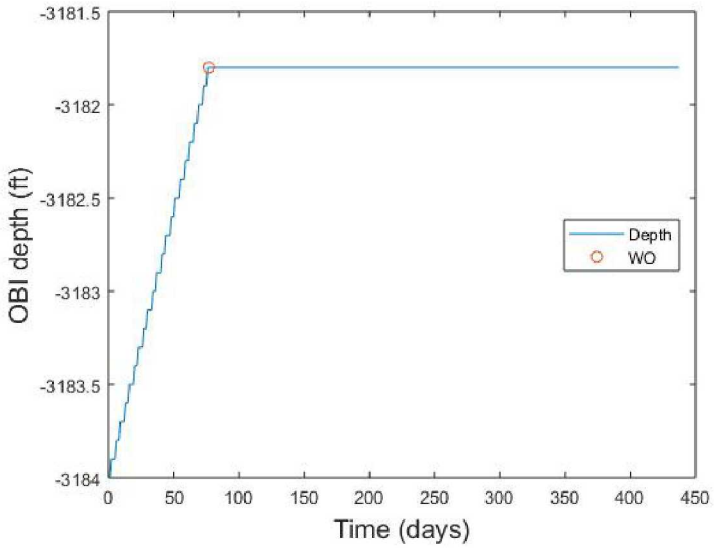

Figure 5-54 OBI depth time history for BM005 simulation.

The outlet specific gravity reached 1.2013, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was nearing completion at the end of the workover. As summarized in Table 5-31, the total amount of raw water injected was 0.12 MMB creating a volume of 0.02 MMB by leaching over 29 ft of the cavern wall out to 3 ft.

Table 5-31 Summary of Simulation Output for BM005

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1959	0.12	0.02	29	3

The simulated cavern shape as a result of the leaching is shown in Figure 5-55. The initial geometry (blue line) is a 2-D axisymmetric representation of the 1987 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-56.

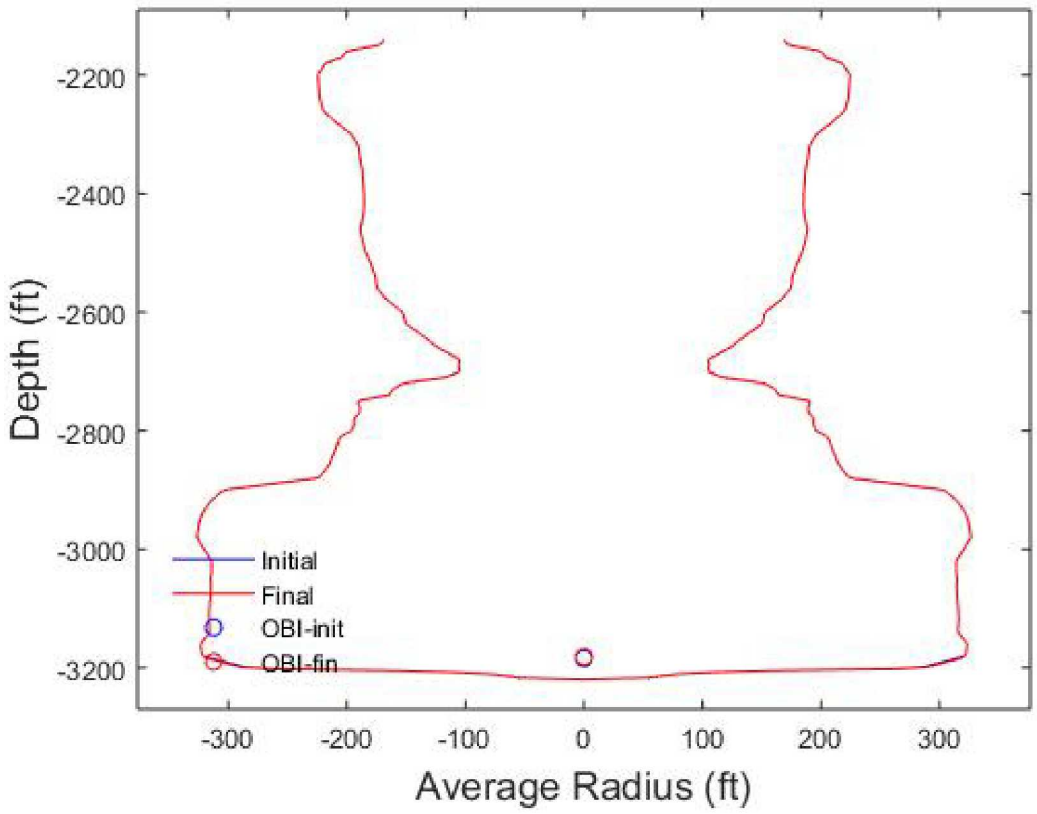

Figure 5-55 Simulated cavern geometry of BM005 with elongated horizontal axis.

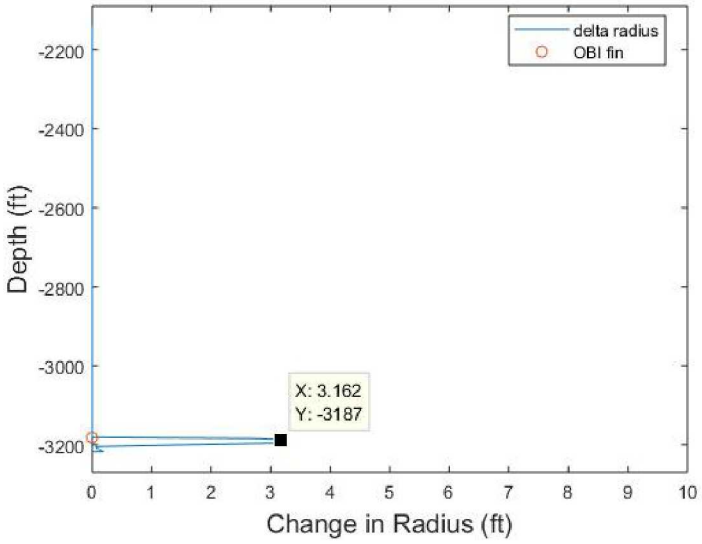

Figure 5-56 Change in radius as a function of depth for BM005.

5.3.2. *BM102*

BM102 had minor water movement in 2017 (see Table 4-3) which is modeled in 1 single stage summarized in Table 5-32. The average injection rate was 9,010 BBls/day over the 47 days of injection. A standard workover duration of 60 days was used at the end of injection. The cumulative injected water volume is shown as a function of time in Figure 5-57. The hanging string was located at 16 ft above the cavern bottom. The initial OBI was 124 ft above the cavern bottom. The evolution of the OBI over time is shown in Figure 5-58.

Table 5-32 Summary of Simulation Input for BM102

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2120	1440	2120	16	124	9010	47	60

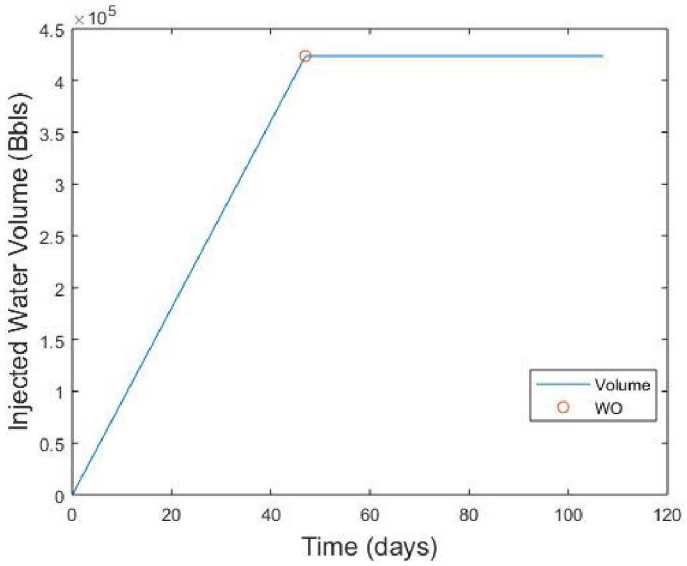

Figure 5-57 Injected water time history for BM102 simulation.

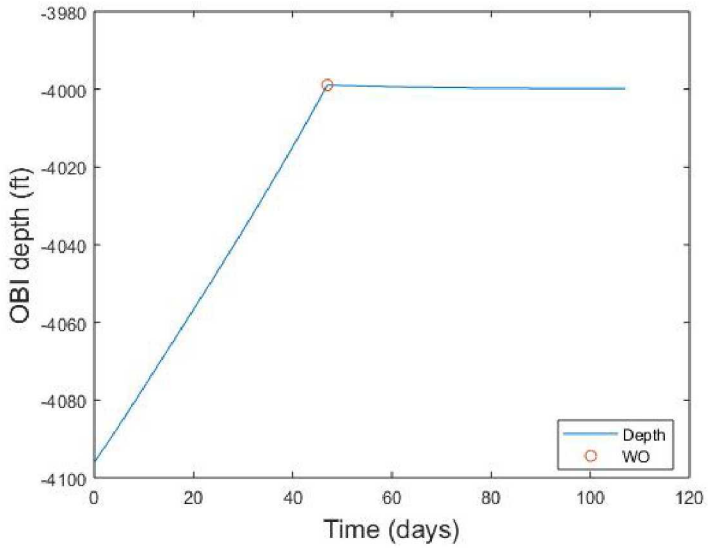

Figure 5-58 OBI depth time history for BM102 simulation.

The outlet specific gravity reached 1.1995, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the workover. As summarized in Table 5-33, the total amount of raw water injected was 0.41 MMB creating a volume of 0.07 MMB by leaching over 210 ft of the cavern wall out to 3 ft.

Table 5-33 Summary of Simulation Output for BM102

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1995	0.41	0.07	210	3

The simulated cavern shape as a result of the leaching is shown in Figure 5-59. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2013 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-60. The leaching widened the cavern foot.

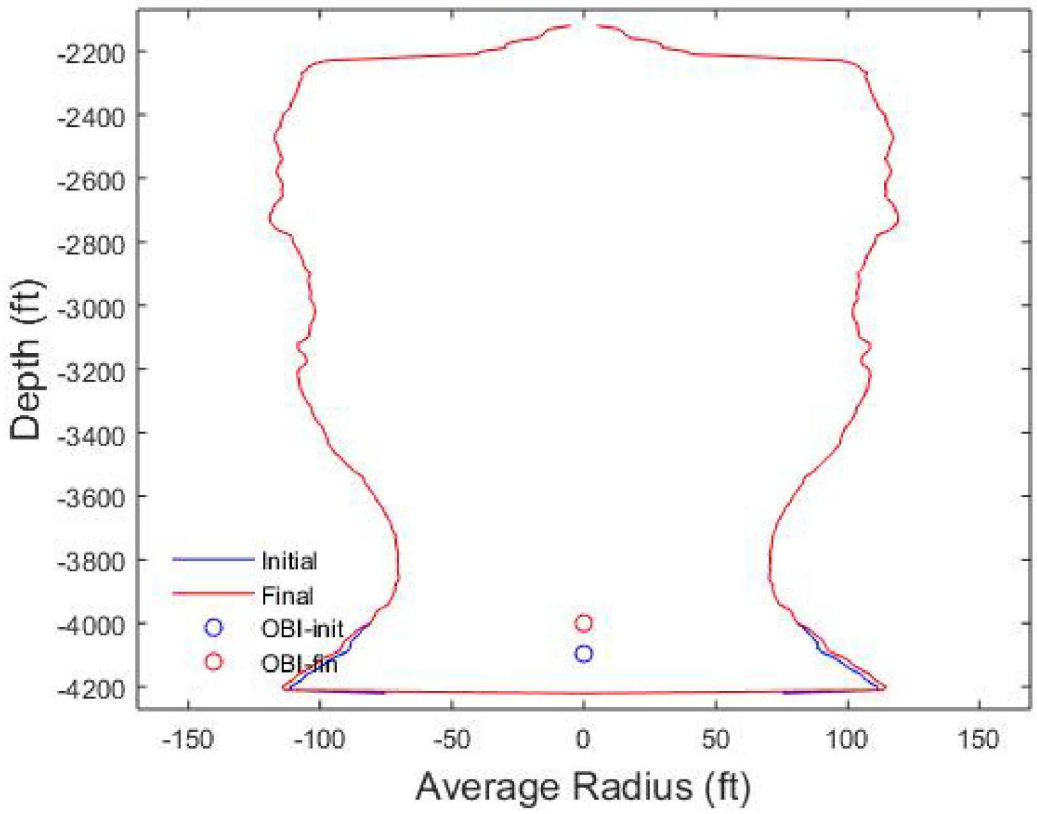

Figure 5-59 Simulated cavern geometry of BM102 with elongated horizontal axis.

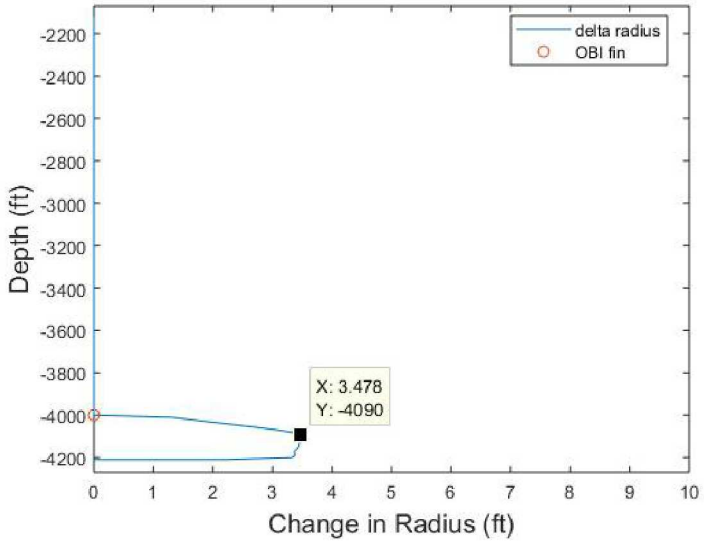

Figure 5-60 Change in radius as a function of depth for BM102.

5.3.3. *BM103*

BM103 had significant water movement in 2017 (see Table 4-3) which is modeled in 2 separate stages summarized in Table 5-34. The average injection rate for the first stage was 16,215 BBls/day over the 67 days of injection. A workover of 52 days was used to finish the first stage as this was the number of days that separated the two injection events. The average injection rate for the second stage was 20,490 BBls/day over the 100 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The cumulative injected water volume is shown as a function of time in Figure 5-61. The hanging string was located at 18 ft above the cavern bottom for stage 1 and 54 ft above the cavern bottom for stage 2. The initial OBI was 65 ft above the cavern bottom for stage 1 and 303 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-62.

Table 5-34 Summary of Simulation Input for BM103

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2110	4010	1900	18	65	16215	67	52
2	2110	4010	1900	54	303	20490	100	60

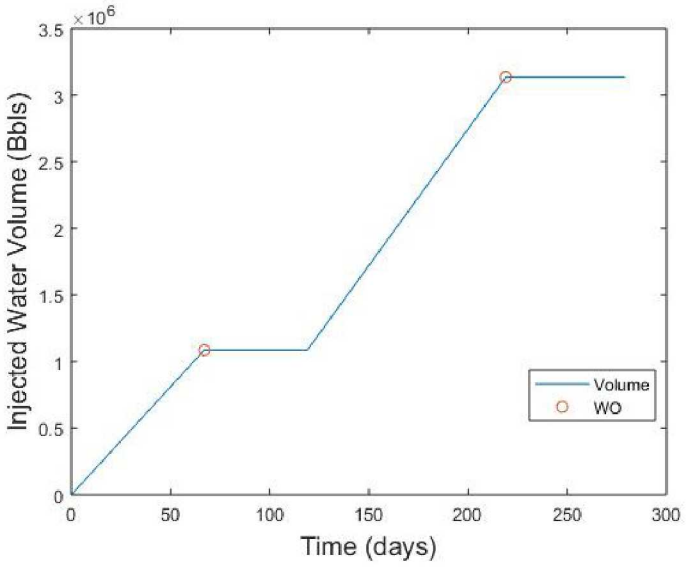

Figure 5-61 Injected water time history for BM103 simulation.

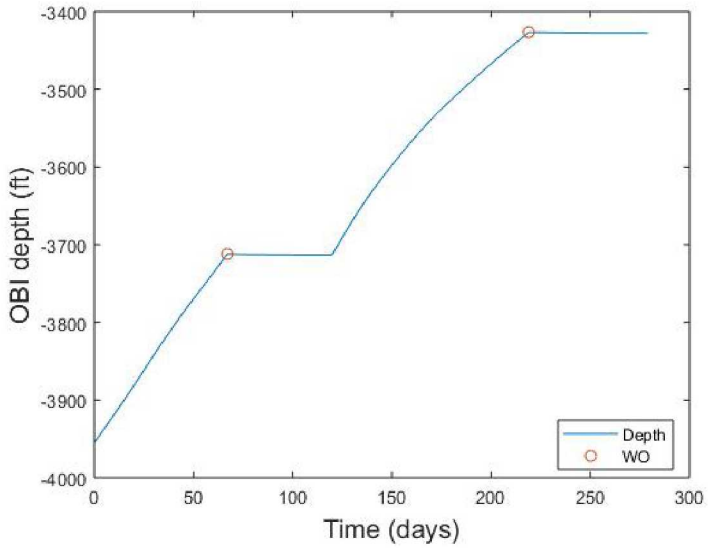

Figure 5-62 OBI depth time history for BM103 simulation.

The outlet specific gravity reached 1.1991, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-35, the total amount of raw water injected was 3.14 MMB creating a volume of 0.52 MMB by leaching over 572 ft of the cavern wall out to 16 ft.

Table 5-35 Summary of Simulation Output for BM103

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1991	3.14	0.52	572	16

The simulated cavern shape as a result of the leaching is shown in Figure 5-63. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2016 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-64.

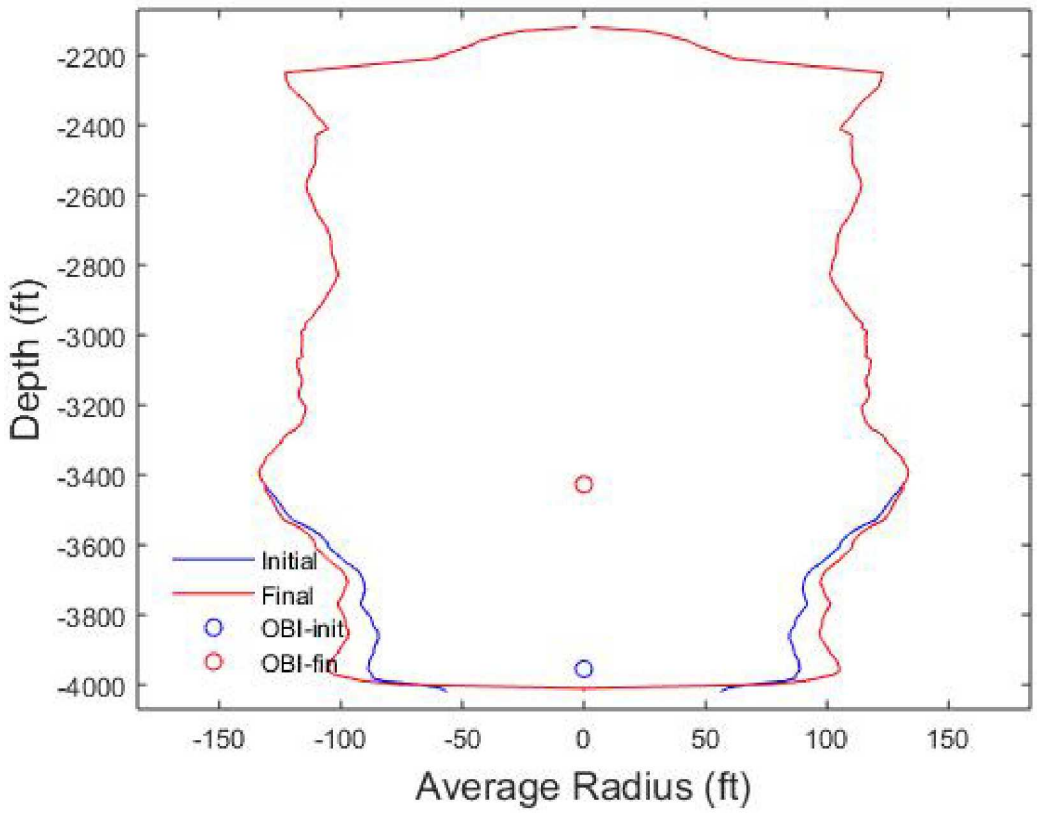

Figure 5-63 Simulated cavern geometry of BM103 with elongated horizontal axis.

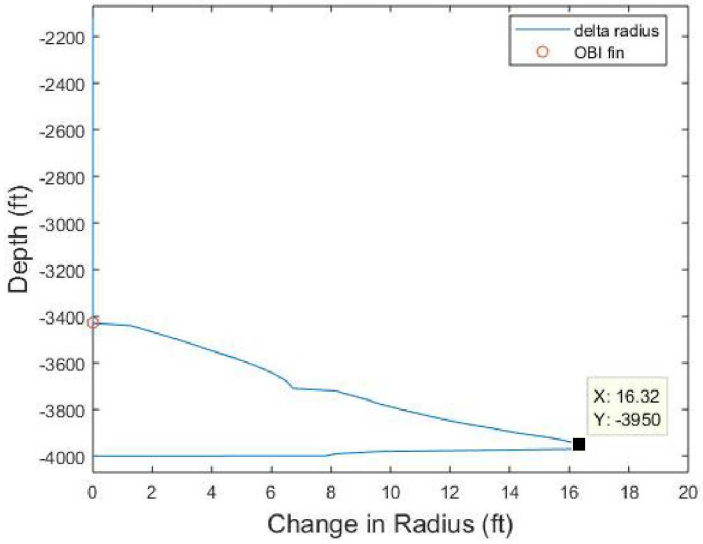

Figure 5-64 Change in radius as a function of depth for BM103.

5.3.4. BM108

BM108 had significant water movement in 2017 (see Table 4-3) which is modeled in 2 separate stages summarized in Table 5-36. The average injection rate for the first stage was 17,448 BBls/day over the 60 days of injection. A workover of 52 days was used to finish the first stage as this was the number of days that separated the two injection events. The average injection rate for the second stage was 15,196 BBls/day over the 109 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The cumulative injected water volume is shown as a function of time in Figure 5-65. The hanging string was located at 16 ft above the cavern bottom for stage 1 and 15 ft above the cavern bottom for stage 2. The initial OBI was 71 ft above the cavern bottom for stage 1 and 188 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-66.

Table 5-36 Summary of Simulation Input for BM108

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2160	4140	1980	16	71	17448	60	52
2	2160	4140	1980	15	188	15196	109	60

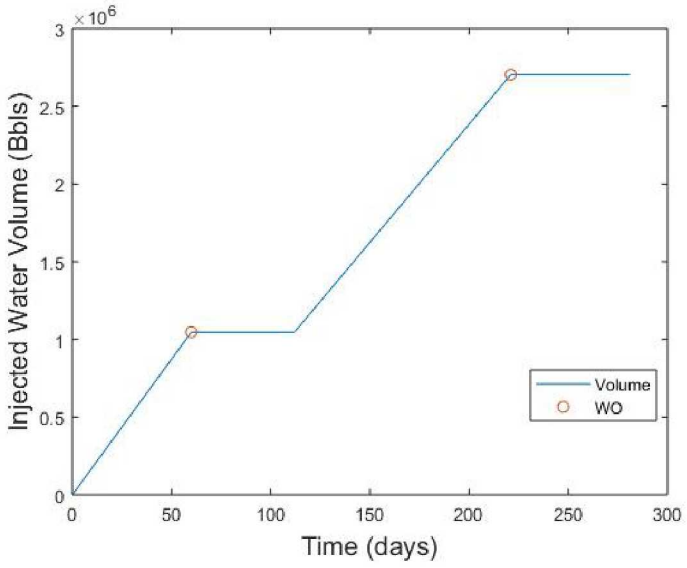

Figure 5-65 Injected water time history for BM108 simulation.

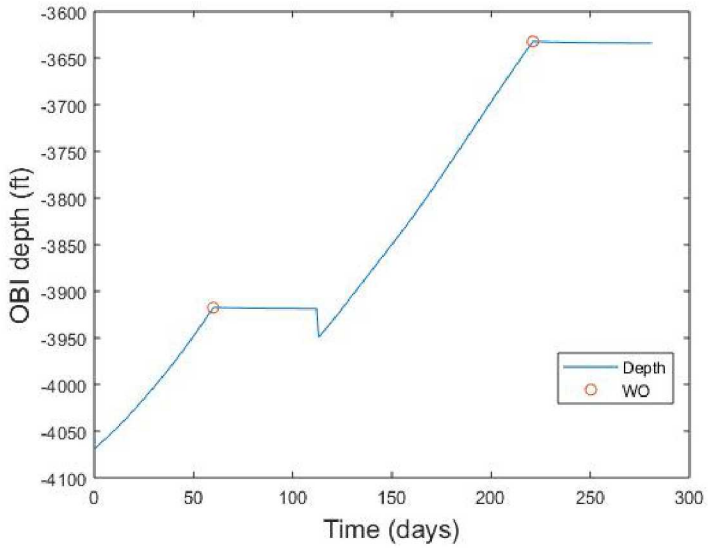

Figure 5-66 OBI depth time history for BM108 simulation.

The outlet specific gravity reached 1.1993, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-37, the total amount of raw water injected was 2.70 MMB creating a volume of 0.44 MMB by leaching over 240 ft of the cavern wall out to 15 ft.

Table 5-37 Summary of Simulation Output for BM108

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1993	2.70	0.44	496	15

The simulated cavern shape as a result of the leaching is shown in Figure 5-67. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2016 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-68. The toe of the cavern had a radius of 126 ft and was the widest part of the cavern to start. After 2017 leaching, the toe now extends 18 ft beyond the next widest part of the cavern.

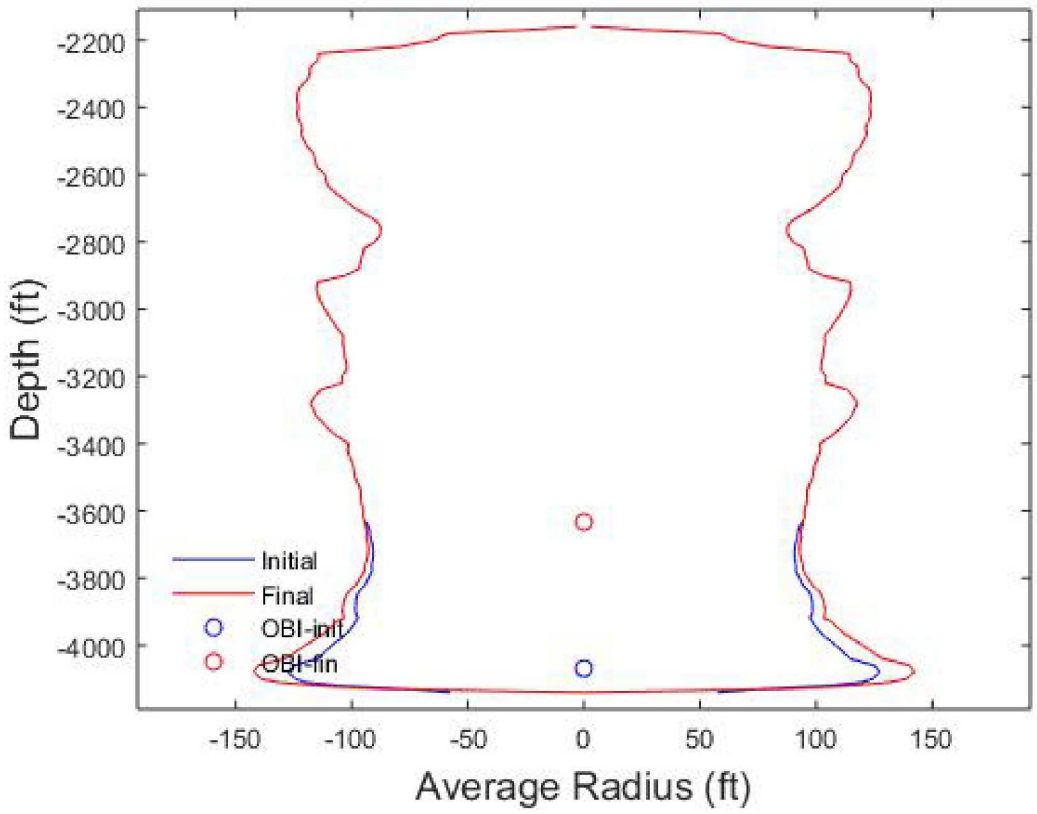

Figure 5-67 Simulated cavern geometry of BM108 with elongated horizontal axis.

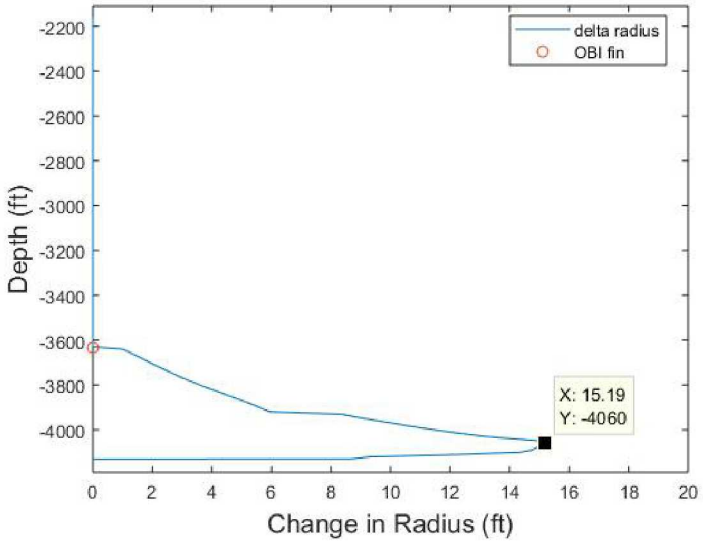

Figure 5-68 Change in radius as a function of depth for BM108.

5.3.5. *BM111*

BM111 had significant water movement in 2017 (see Table 4-3) which is modeled in 2 separate stages summarized in Table 5-38. The average injection rate for the first stage was 19,122 BBls/day over the 60 days of injection. A workover of 52 days was used to finish the first stage as this was the number of days that separated the two injection events. The average injection rate for the second stage was 21,344 BBls/day over the 100 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The cumulative injected water volume is shown as a function of time in Figure 5-69. The hanging string was located at 11 ft above the cavern bottom for stage 1 and 15 ft above the cavern bottom for stage 2. The initial OBI was 48 ft above the cavern bottom for stage 1 and 287 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-70.

Table 5-38 Summary of Simulation Input for BM111

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2120	4120	2000	11	48	19122	60	52
2	2120	4120	2000	15	287	21344	100	60

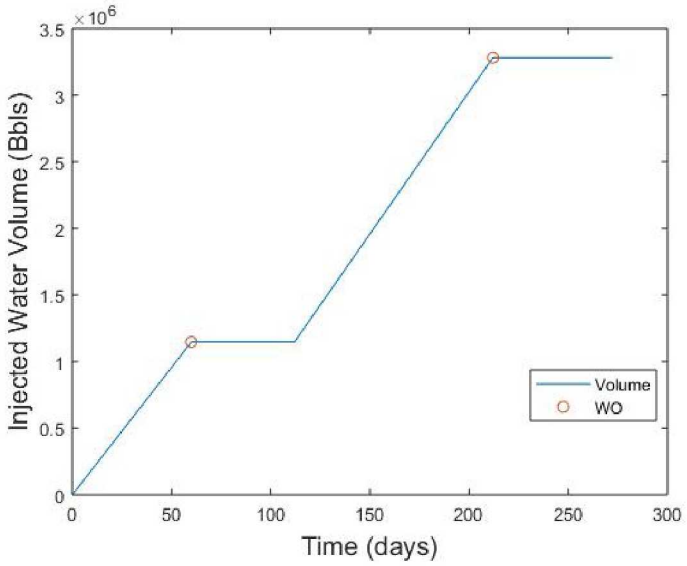

Figure 5-69 Injected water time history for BM111 simulation.

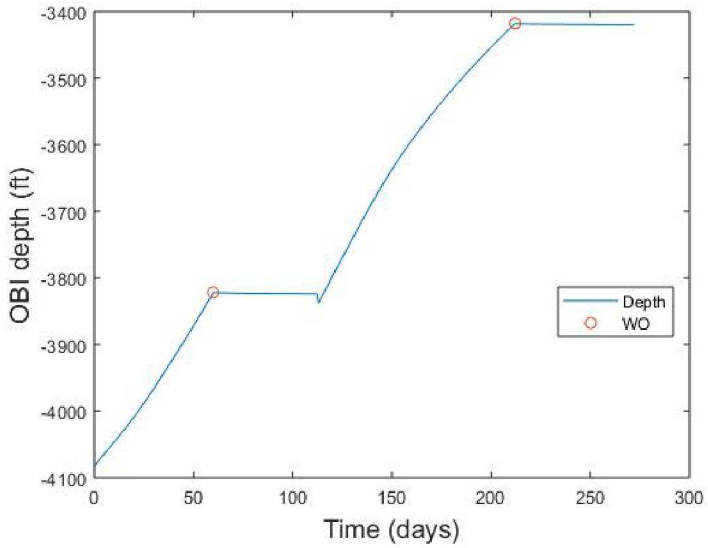

Figure 5-70 OBI depth time history for BM111 simulation.

The outlet specific gravity reached 1.1997, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-39, the total amount of raw water injected was 3.28 MMB creating a volume of 0.54 MMB by leaching over 701 ft of the cavern wall out to 16 ft.

Table 5-39 Summary of Simulation Output for BM111

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1997	3.28	0.54	701	16

The simulated cavern shape as a result of the leaching is shown in Figure 5-71. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2016 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-72. The cavern foot was significantly widened.

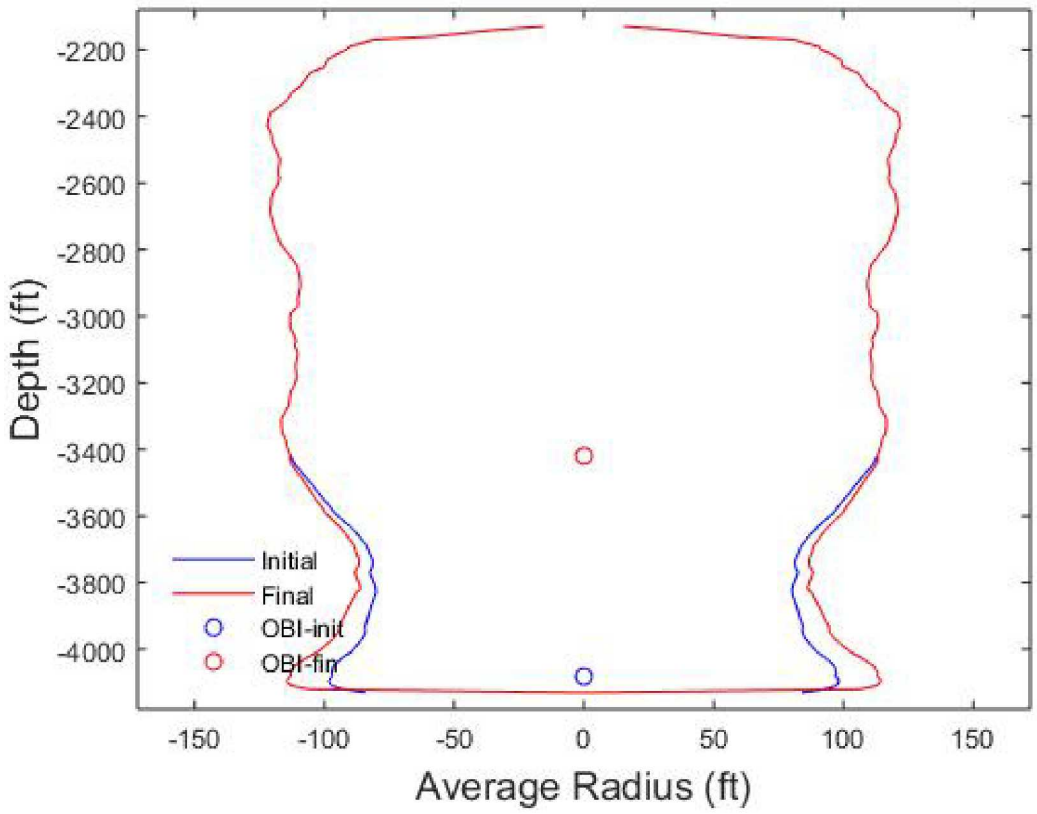

Figure 5-71 Simulated cavern geometry of BM111 with elongated horizontal axis.

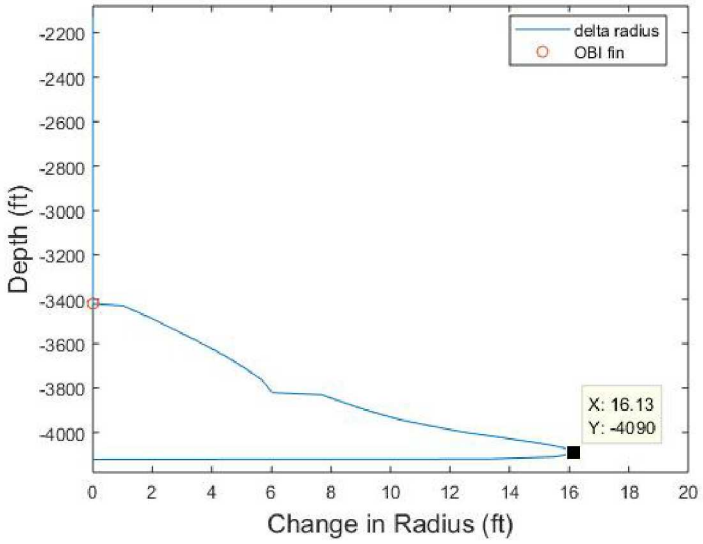

Figure 5-72 Change in radius as a function of depth for BM111.

5.3.6. *BM113*

BM113 had minor water movement in 2017 (see Table 4-3) which is modeled in 1 stage summarized in Table 5-40. The average injection rate for the stage was 20,569 BBls/day over the 11 days of injection. A standard workover of 60 days was used to finish the stage. The cumulative injected water volume is shown as a function of time in Figure 5-73. The hanging string was located at 395 ft above the cavern bottom. The initial OBI was 915 ft above the cavern bottom. The evolution of the OBI over time is shown in Figure 5-74.

Table 5-40 Summary of Simulation Input for BM113

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2470	4020	1550	395	915	20569	11	60

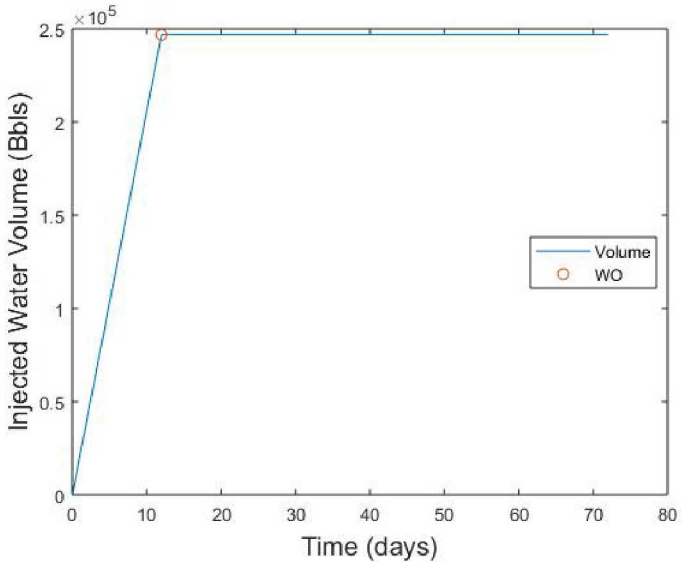

Figure 5-73 Injected water time history for BM113 simulation.

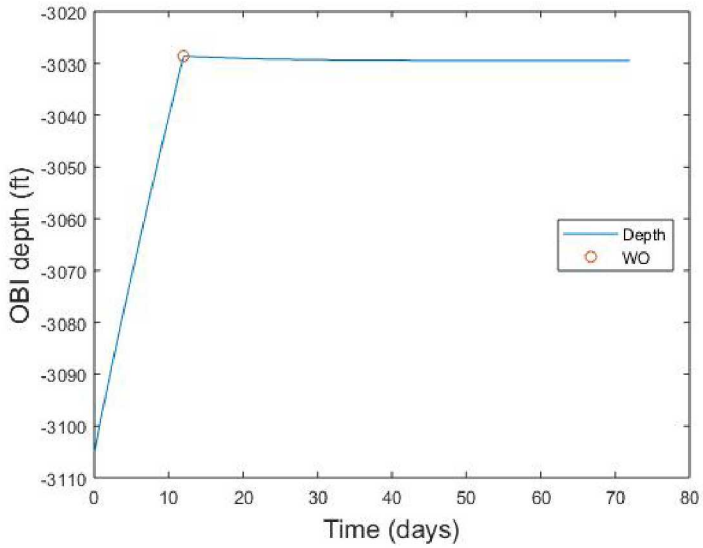

Figure 5-74 OBI depth time history for BM113 simulation.

The outlet specific gravity reached 1.2010, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the workover. As summarized in Table 5-41, the total amount of raw water injected was 0.25 MMB creating a volume of 0.04 MMB by leaching over 960 ft of the cavern wall out to 1 ft.

Table 5-41 Summary of Simulation Output for BM113

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2010	0.25	0.04	960	1

The simulated cavern shape as a result of the leaching is shown in Figure 5-75. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2012 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred in a zone between 370 ft and 930 ft above the cavern bottom, as shown in Figure 5-76. The large distance of the hanging string and OBI from the cavern bottom resulted in a leaching pattern above the cavern foot.

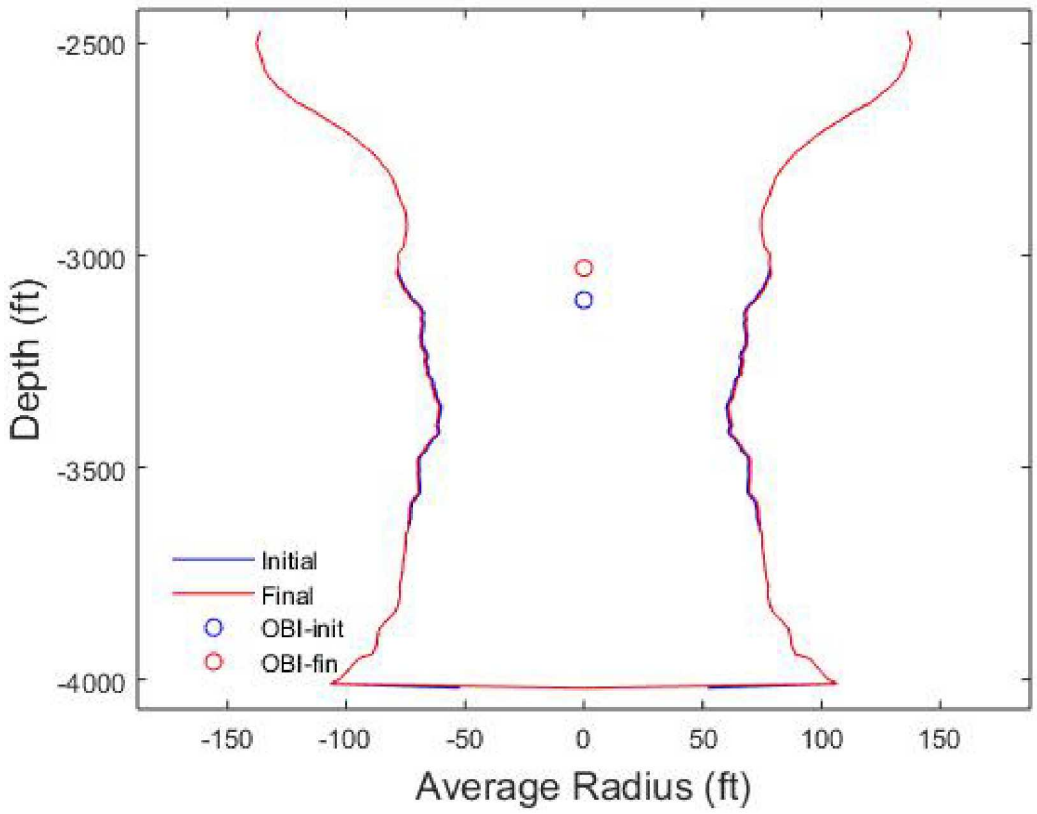

Figure 5-75 Simulated cavern geometry of BM113 with elongated horizontal axis.

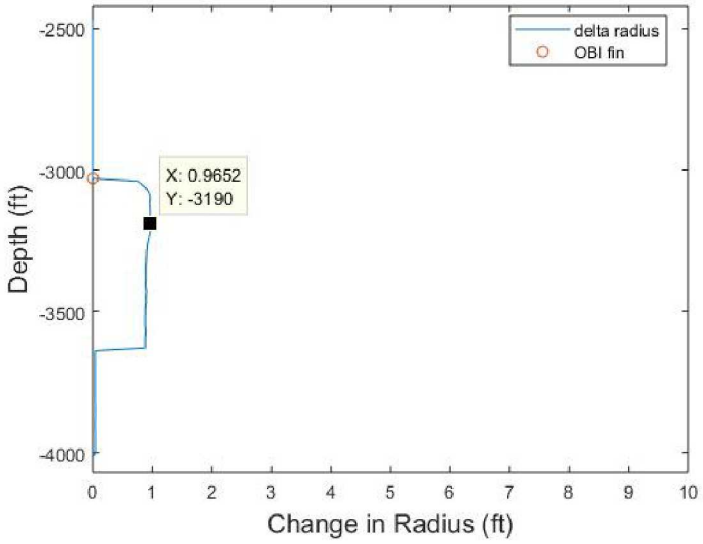

Figure 5-76 Change in radius as a function of depth for BM113.

5.3.7. *BM114*

BM114 had significant water movement in 2012 and 2017 (see Table 4-3) which is modeled in 3 separate stages summarized in Table 5-42. The average injection rate for the first stage was 89,336 BBls/day over the 10 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 22,081 BBls/day over the 12 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The average injection rate for the third stage was 4,202 BBls/day over the 2 day injection period. A standard workover duration of 60 days was also used at the end of stage 3. The cumulative injected water volume is shown as a function of time in Figure 5-77. The hanging string was located at 13 ft above the cavern bottom for stage 1 and 6 ft above the cavern bottom for stages 2 and 3. The initial OBI was 1480 ft above the cavern bottom for stage 1, 123 ft above the cavern bottom for stage 2, and 198 ft above the cavern bottom for stage 3. The evolution of the OBI over time is shown in Figure 5-78.

Table 5-42 Summary of Simulation Input for BM114

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2140	4110	1970	13	1480	89336	10	60
2	2140	4110	1970	6	123	22081	12	60
3	2140	4110	1970	6	198	4202	2	60

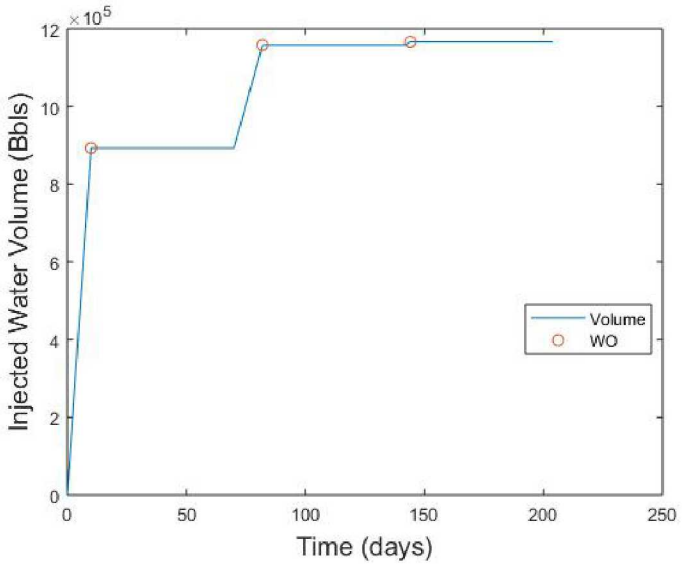

Figure 5-77 Injected water time history for BM114 simulation.

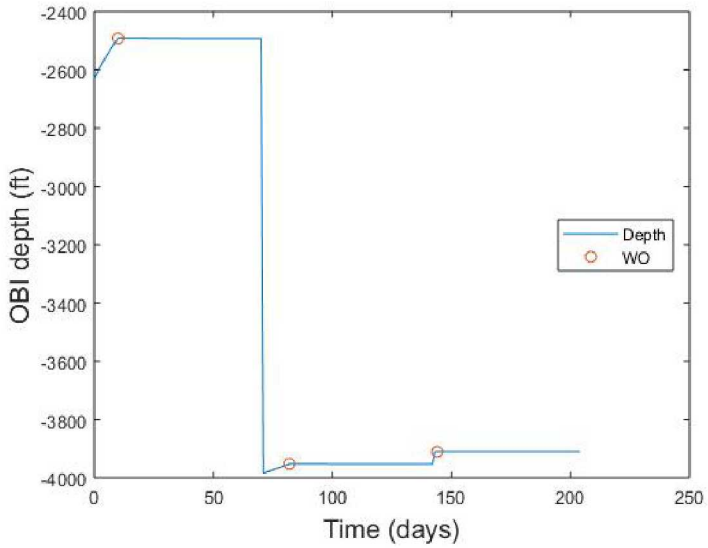

Figure 5-78 OBI depth time history for BM114 simulation.

The outlet specific gravity reached 1.2019, equivalent to the value of 1.2019 expected for salt saturated water, suggesting that leaching was complete at the end of the stage 3 workover. As summarized in Table 5-43, the total amount of raw water injected was 1.16 MMB creating a volume of 0.19 MMB by leaching over 1650 ft of the cavern wall out to 3 ft.

Table 5-43 Summary of Simulation Output for BM114

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2019	1.16	0.19	1650	3

The simulated cavern shape as a result of the leaching is shown in Figure 5-79. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2012 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-80. The three stage leach with significant changes in the OBI depth but without major changes in the hanging string depth resulted in a relatively small widening of the cavern foot, given the total volume of water injected. Most of the leaching was spread over a relatively large vertical extent of 1650 ft, minimizing growth at the foot.

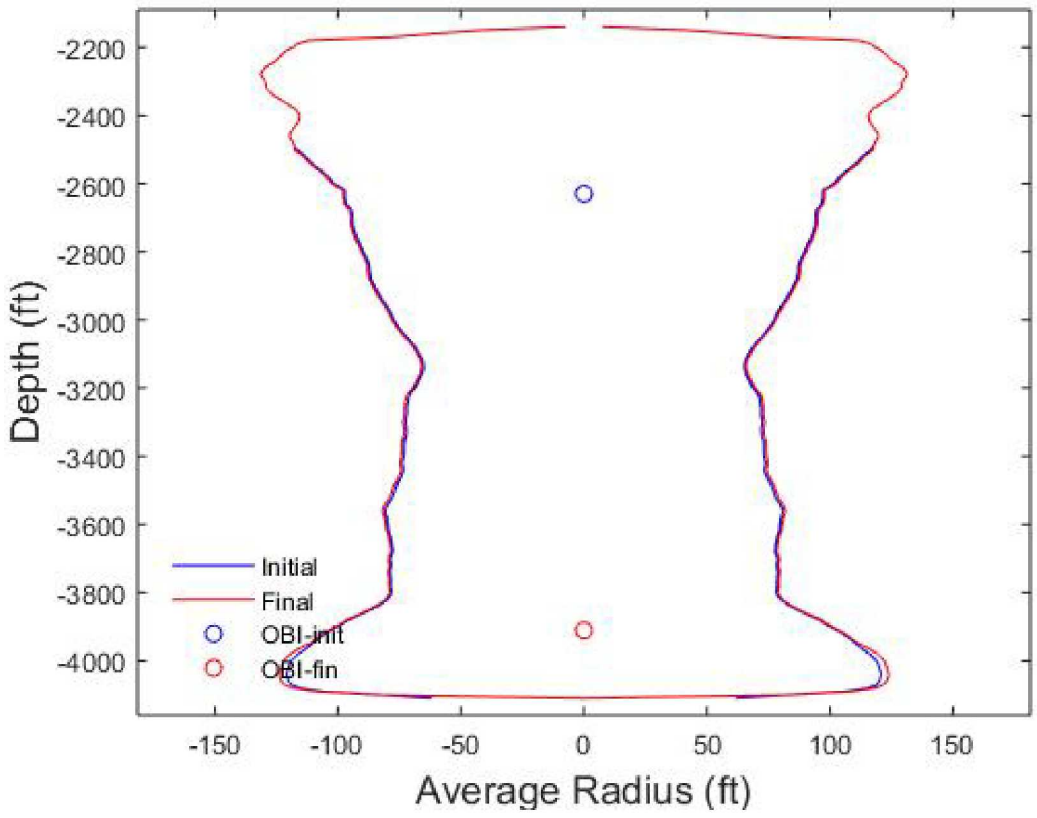

Figure 5-79 Simulated cavern geometry of BM114 with elongated horizontal axis.

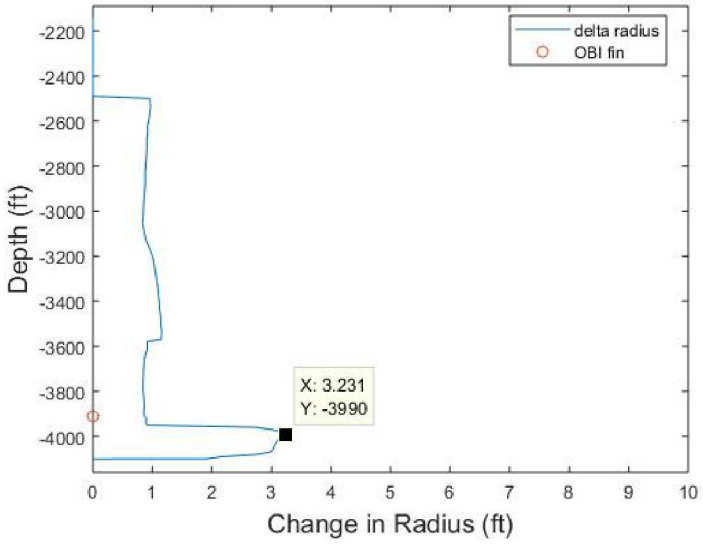

Figure 5-80 Change in radius as a function of depth for BM114.

5.3.8. *BM115*

BM115 had a minor amount of water movement in 2017 (see Table 4-3) which is modeled in 2 separate stages summarized in Table 5-44. The average injection rate for the first stage was 30,741 BBls/day over the 12 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 4,418 BBls/day over the 15 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The cumulative injected water volume is shown as a function of time in Figure 5-81. The hanging string was located at 20 ft above the cavern bottom for both stages. The initial OBI was 44 ft above the cavern bottom for stage 1 and 97 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-82.

Table 5-44 Summary of Simulation Input for BM115

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2020	4090	2070	20	44	30741	12	60
2	2020	4090	2070	20	97	4418	15	60

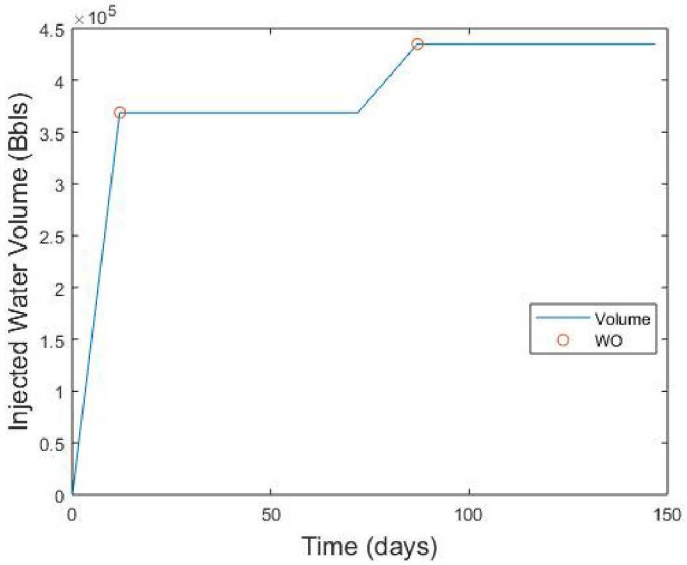

Figure 5-81 Injected water time history for BM115 simulation.

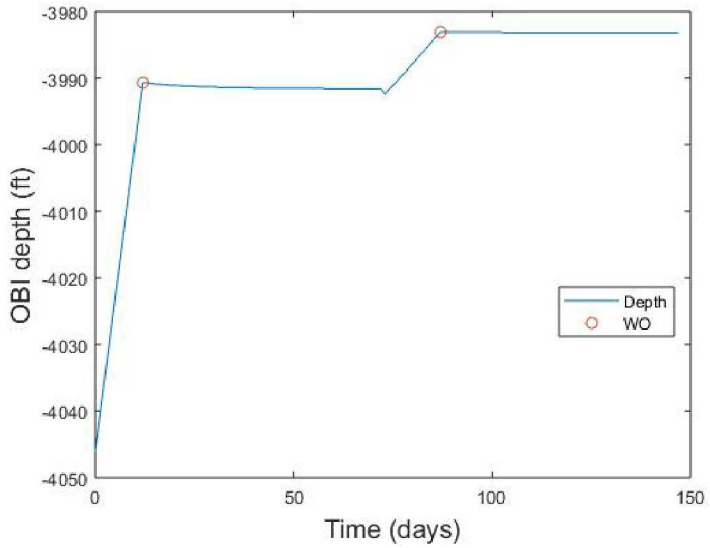

Figure 5-82 OBI depth time history for BM115 simulation.

The outlet specific gravity reached 1.1990, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-45, the total amount of raw water injected was 0.43 MMB creating a volume of 0.07 MMB by leaching over 97 ft of the cavern wall out to 7 ft.

Table 5-45 Summary of Simulation Output for BM115

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
0.1990	0.43	0.07	97	7

The simulated cavern shape as a result of the leaching is shown in Figure 5-83. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2011 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-84. The two stage leach without a change in the hanging string depth resulted in a widening of the cavern foot.

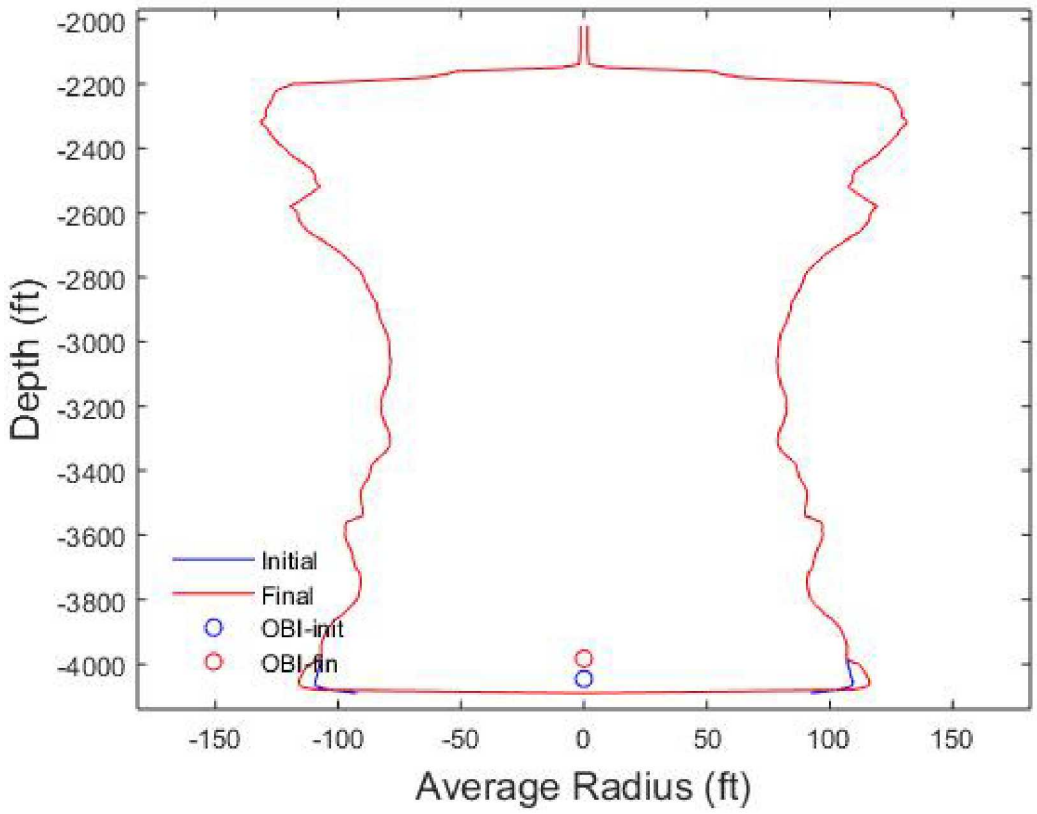

Figure 5-83 Simulated cavern geometry of BM115 with elongated horizontal axis.

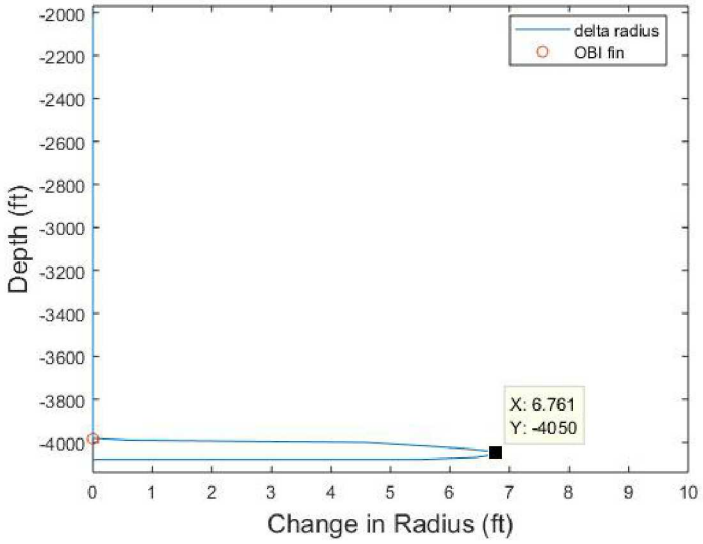

Figure 5-84 Change in radius as a function of depth for BM115.

5.3.9. BM116

BM116 had significant water movement in 2012 and 2017 (see Table 4-3) which is modeled in 3 separate stages summarized in Table 5-46. The average injection rate for the first stage was 37,105 BBls/day over the 14 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 33,337 BBls/day over the 23 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The average injection rate for the third stage was 26,394 BBls/day over the 12 day injection period. A standard workover duration of 60 days was also used at the end of stage 3. The cumulative injected water volume is shown as a function of time in Figure 5-85. The hanging string was located at 224 ft above the cavern bottom for stage 1, 20 ft above the cavern bottom for stage 2, and 17 feet above the cavern bottom for stage 3. The initial OBI was 741 ft above the cavern bottom for stage 1, 841 ft above the cavern bottom for stage 2, and 697 ft above the cavern bottom for stage 3. The evolution of the OBI over time is shown in Figure 5-86. The sharp changes in OBI depth at the end of stage 2 represents a time where the simulated OBI depth at the end of the stage exceeds the measured depth at the beginning of the following stage.

Table 5-46 Summary of Simulation Input for BM116

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2100	4228	2128	224	741	37105	14	60
2	2100	4235	2135	20	841	33337	23	60
3	2100	4232	2132	17	697	26394	12	60

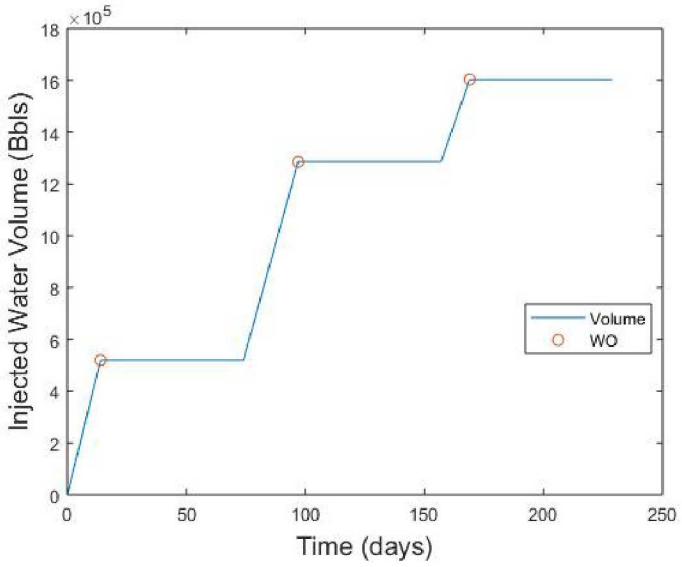

Figure 5-85 Injected water time history for BM116 simulation.

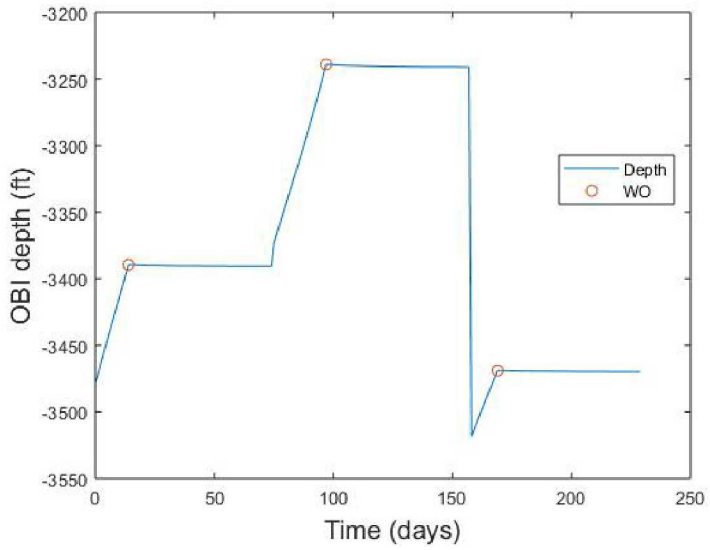

Figure 5-86 OBI depth time history for BM116 simulation.

The outlet specific gravity reached 1.2005, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 3 workover. As summarized in Table 5-47, the total amount of raw water injected was 1.60 MMB creating a volume of 0.26 MMB by leaching over 1000 ft of the cavern wall out to 4 ft.

Table 5-47 Summary of Simulation Output for BM116

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2005	1.60	0.26	1000	4

The simulated cavern shape as a result of the leaching is shown in Figure 5-87. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2011 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred 700 ft above base of the cavern, as shown in Figure 5-88. The three stage leach with a change in the hanging string depth and OBI resulted in a multileveled leaching pattern.

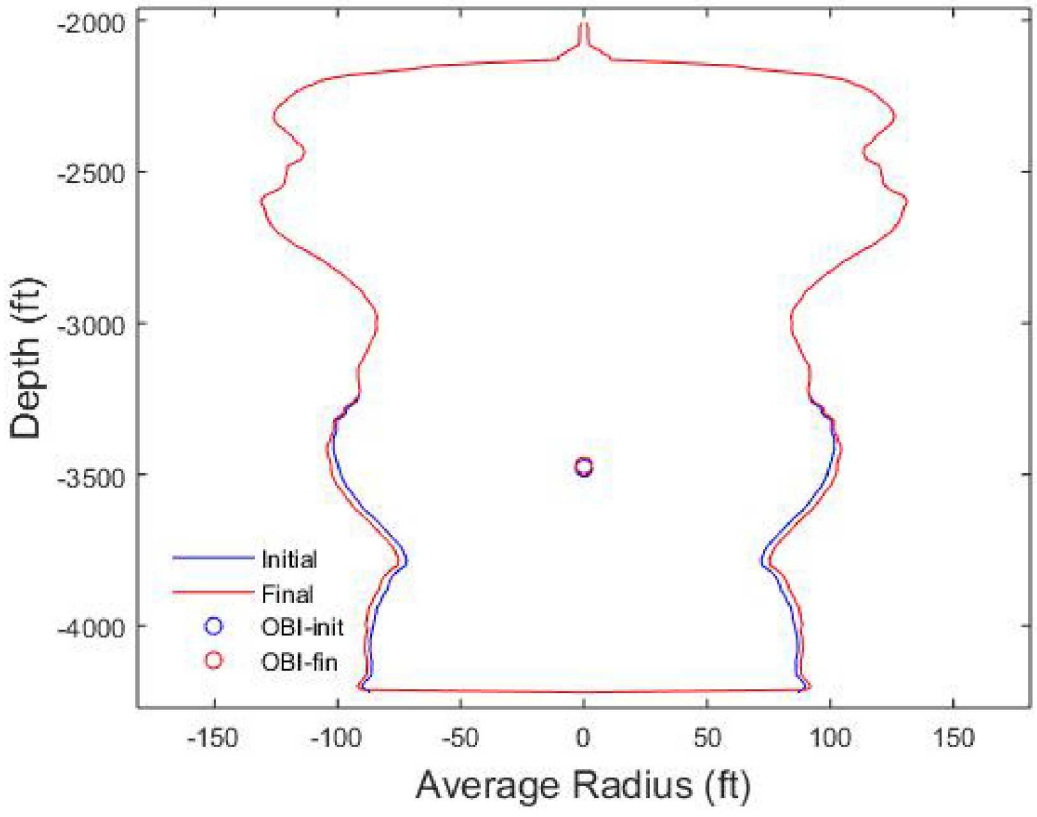

Figure 5-87 Simulated cavern geometry of BM116 with elongated horizontal axis.

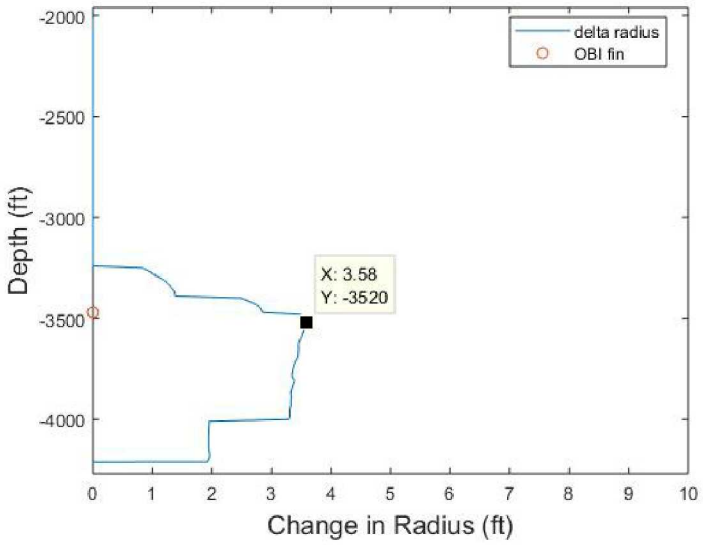

Figure 5-88 Change in radius as a function of depth for BM116.

5.4. West Hackberry

Simulation results for West Hackberry are summarized in Table 5-48. One cavern, WH111, has had more than 3MMB of water injected since the last sonar.

Table 5-48 Summary of Simulation Results for West Hackberry

Cavern	Latest sonar	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Maximum Change in Radius (ft)
WH011	2013+	2.05	0.33	20
WH103	2014	1.68	0.27	13
WH109	2016	1.70	0.28	16
WH111	2015	3.88	0.63	5
WH113	2014	0.93	0.15	11
WH114	2015	2.90	0.49	17

Shading denotes caverns with more than 3 MMB of injected raw water
+Sonar in 2018 following 2017 sales/exchange

5.4.1. WH011

WH011 had significant water movement in 2014 and 2017 (see Table 4-4) which is modeled in 2 separate stages summarized in Table 5-49. The average injection rate for the first stage was 14,224 BBls/day over the 8 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 29,371 BBls/day over the 66 day injection period. A standard workover

duration of 60 days was also used at the end of stage 2. The cumulative injected water volume is shown as a function of time in Figure 5-89. The hanging string was located at 20 ft and 15 ft above the cavern bottom for stages 1 and 2, respectively. The initial OBI was 34 ft above the cavern bottom for stage 1 and 44 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-90.

Table 5-49 Summary of Simulation Input for WH011

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2810	3750	940	20	34	14224	8	60
2	2810	3750	940	15	44	29371	66	60

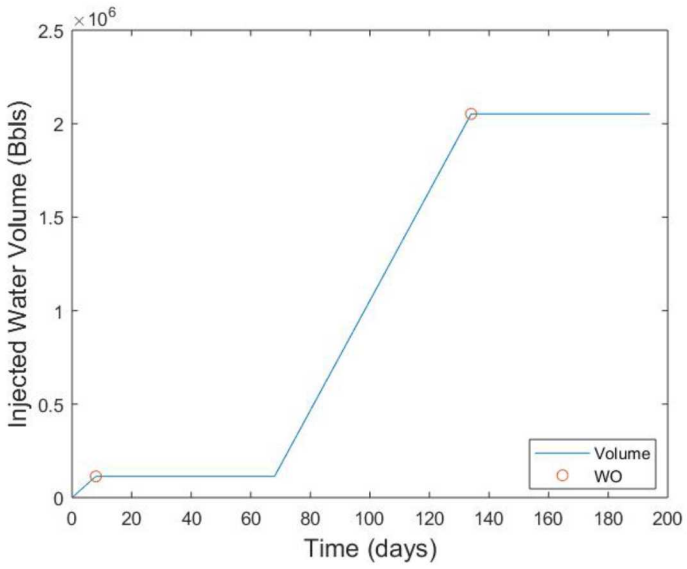

Figure 5-89 Injected water time history for WH011 simulation.

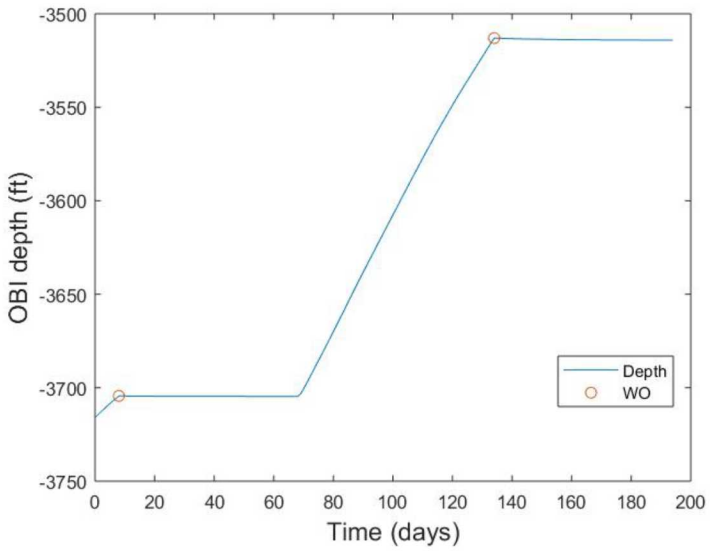

Figure 5-90 OBI depth time history for WH011 simulation.

The outlet specific gravity reached 1.1951, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-50, the total amount of raw water injected was 2.05 MMB creating a volume of 0.33 MMB by leaching over 216 ft of the cavern wall out to 20 ft.

Table 5-50 Summary of Simulation Output for WH011

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1951	2.05	0.33	216	20

The simulated cavern shape as a result of the leaching is shown in Figure 5-91. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2013 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-92. The two stage leach without a significant change in the OBI or hanging string depths resulted in a widening of the cavern floor. After 2017 leaching, the toe of the cavern is now the widest part of the cavern, extending ~10 ft beyond the next widest point.

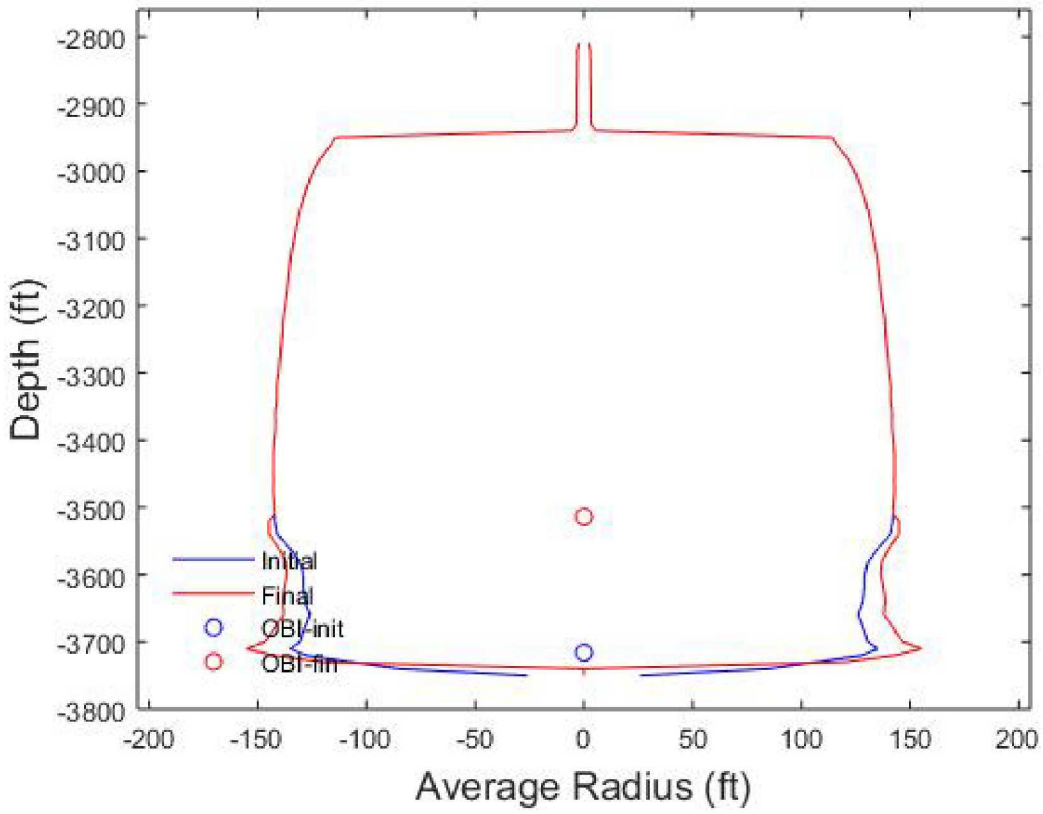

Figure 5-91 Simulated cavern geometry of WH011 with elongated horizontal axis.

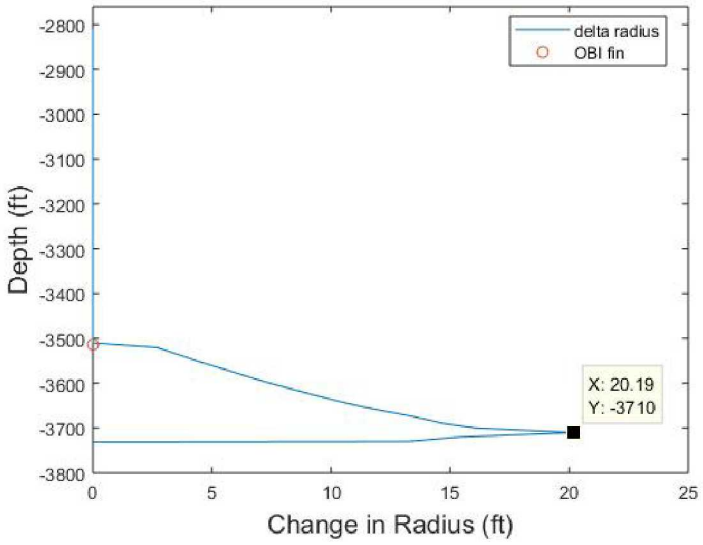

Figure 5-92 Change in radius as a function of depth for WH011.

5.4.2. *WH103*

WH103 had significant water movement in 2016 and 2017 (see Table 4-4) which is modeled in 3 separate stages summarized in Table 5-51. The average injection rate for the first stage was 55,490 BBls/day over the 11 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for the second stage was 16,111 BBls/day over the 55 day injection period. A standard workover duration of 60 days was also used at the end of stage 2. The average injection rate for the third stage was 45,886 BBls/day over the 4 day injection period. A standard workover duration of 60 days was also used at the end of stage 3. The cumulative injected water volume is shown as a function of time in Figure 5-93. The hanging string was located at 18 ft above the cavern bottom for all three stages. The initial OBI was 52 ft above the cavern bottom for stage 1, 110 ft above the cavern bottom for stage 2, and 218 ft above the cavern bottom for stage 3. The evolution of the OBI over time is shown in Figure 5-94. The sharp changes in OBI depth at the end of stages 1 and 2 represent times where the simulated OBI depth at the end of the stage exceeds the measured depth at the beginning of the following stage.

Table 5-51 Summary of Simulation Input for WH103

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2440	4330	1890	18	52	55490	11	60
2	2440	4330	1890	18	110	16111	55	60
3	2440	4330	1890	18	218	45886	4	60

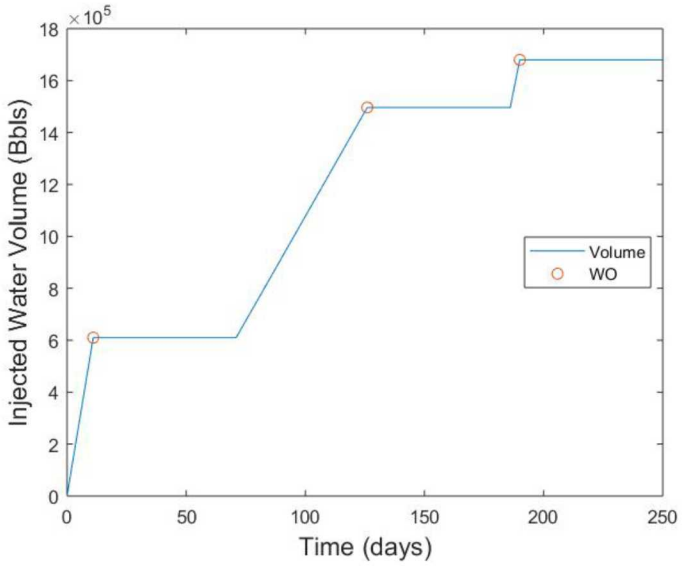

Figure 5-93 Injected water time history for WH103 simulation.

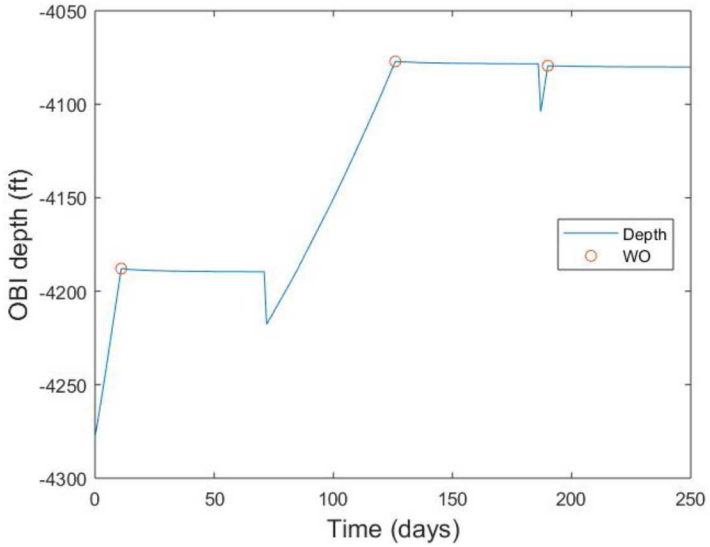

Figure 5-94 OBI depth time history for WH103 simulation.

The outlet specific gravity reached 1.1995, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 3 workover. As summarized in Table 5-52, the total amount of raw water injected was 1.68 MMB creating a volume of 0.27 MMB by leaching over 240 ft of the cavern wall out to 13 ft.

Table 5-52 Summary of Simulation Output for WH103

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1995	1.68	0.27	240	13

The simulated cavern shape as a result of the leaching is shown in Figure 5-95. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2014 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-96. The three stage leach without a change in the hanging string depth resulted in a widening of the cavern floor.

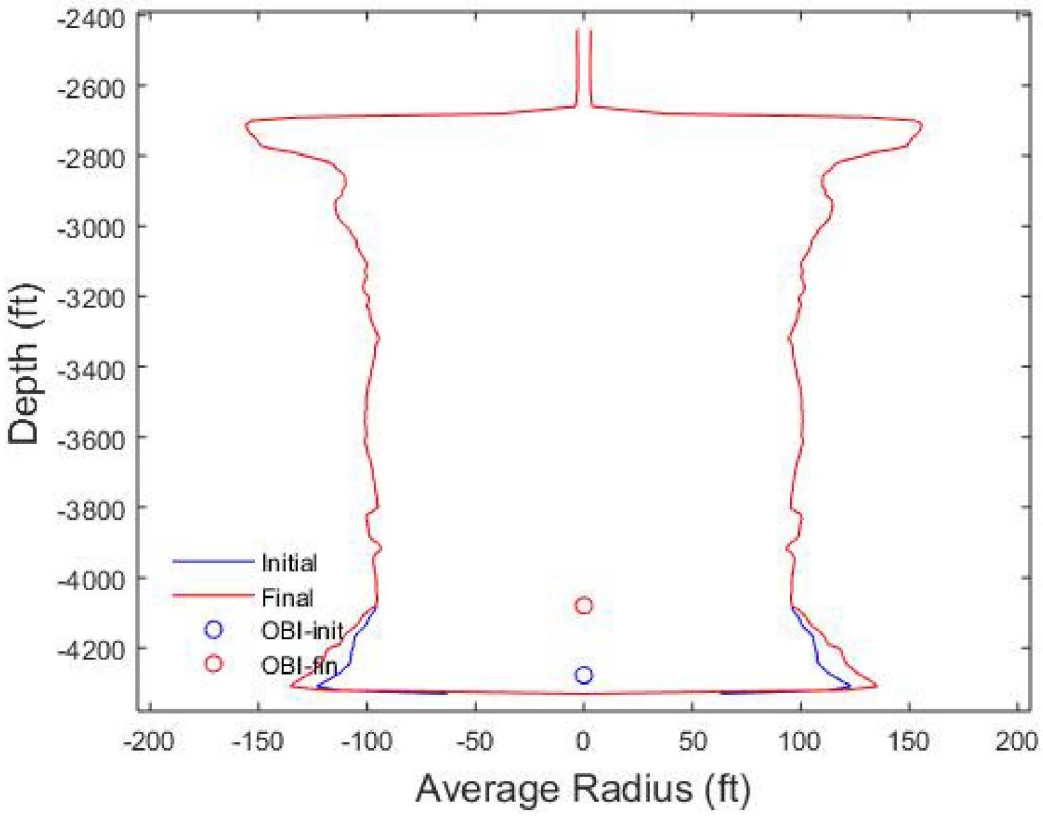

Figure 5-95 Simulated cavern geometry of WH103 with elongated horizontal axis.

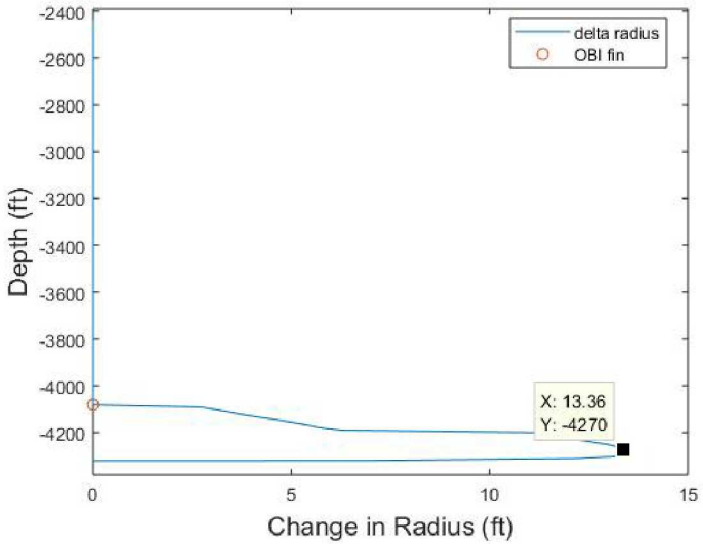

Figure 5-96 Change in radius as a function of depth for WH103.

5.4.3. *WH109*

WH109 had water movement in 2017 (see Table 4-4) that was modeled in 2 stages summarized in Table 5-53. The average injection rate for stage 1 was 10,821 BBls/day over the 11 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for stage 2 was 11,312 BBls/day over the 140 days of injection. A standard workover of 60 days was also used to finish the second stage. The cumulative injected water volume is shown as a function of time in Figure 5-97. The hanging string was located at 262 ft and 18 ft above the cavern bottom for stages 1 and 2, respectively. The initial OBI was 119 ft above the cavern bottom for stage 1. The final OBI depth calculated for stage 1 was used as the initial OBI depth for stage 2. The evolution of the OBI over time is shown in Figure 5-98.

Table 5-53 Summary of Simulation Input for WH109

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2470	4570	2100	262	119	10821	11	60
2	2470	4570	2100	18	--	11312	140	60

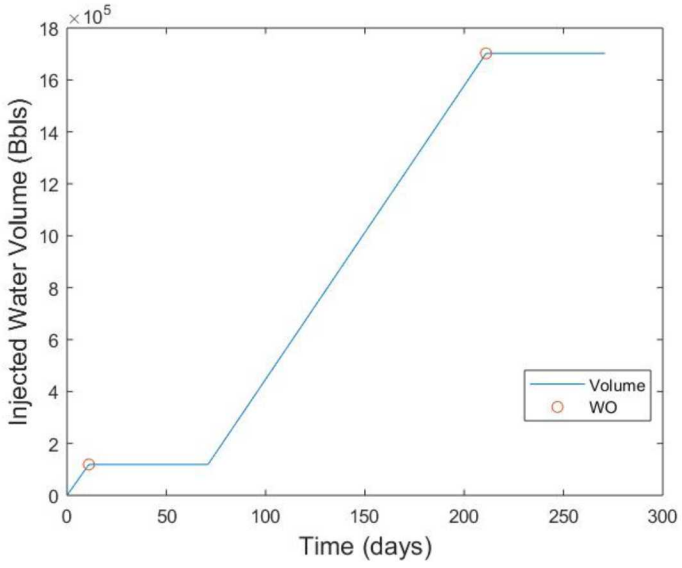

Figure 5-97 Injected water time history for WH109 simulation.

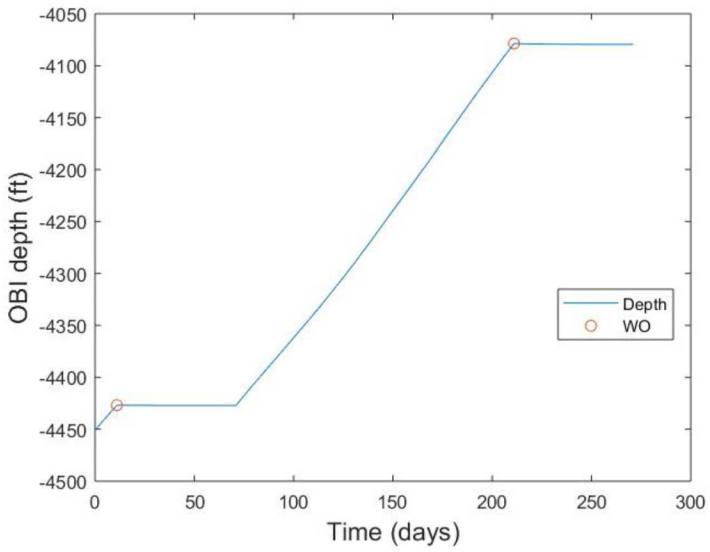

Figure 5-98 OBI depth time history for WH109 simulation.

The outlet specific gravity reached 1.1997, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 1 workover. As summarized in Table 5-54, the total amount of raw water injected was 1.70 MMB creating a volume of 0.28 MMB by leaching over 451 ft of the cavern wall out to 16 ft.

Table 5-54 Summary of Simulation Output for WH109

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1997	1.70	0.28	451	16

The simulated cavern shape as a result of the leaching is shown in Figure 5-99. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2016 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred 240 ft above the base of the cavern, as shown in Figure 5-100. The two stage leach with significant changes in the OBI and hanging string depth resulted in a very non-uniform leach of the cavern wall near the cavern floor.

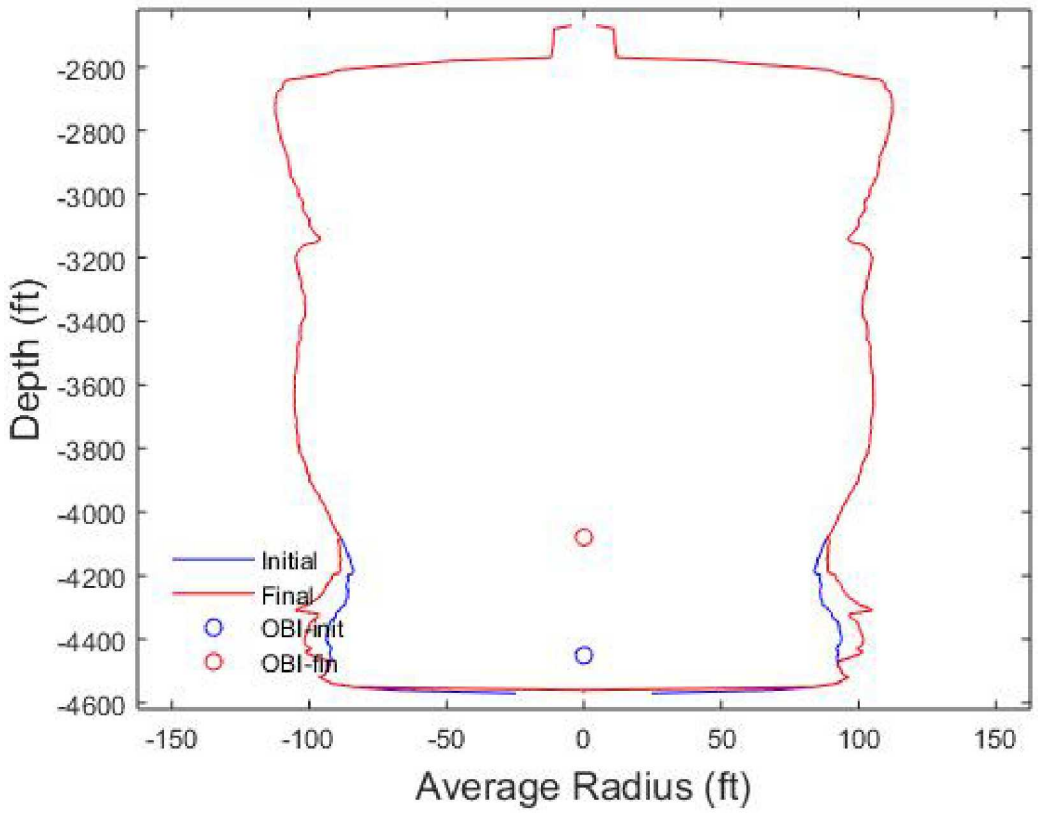

Figure 5-99 Simulated cavern geometry of WH109 with elongated horizontal axis.

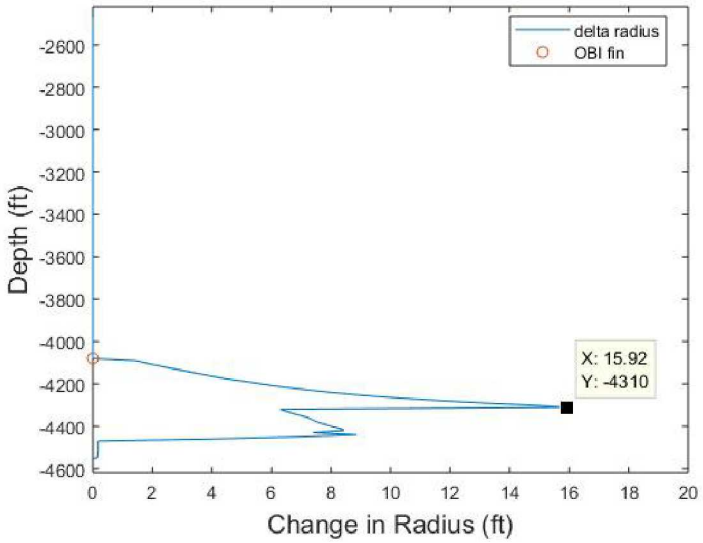

Figure 5-100 Change in radius as a function of depth for WH109.

5.4.4. WH111

WH111 had water movement in 2017 (see Table 4-4) that was modeled in 3 stages summarized in Table 5-55. The average injection rate for stage 1 was 75,749 BBls/day over the 5 days of injection. A standard workover of 60 days was used to finish the first stage. The average injection rate for stage 2 was 39,597 BBls/day over the 44 days of injection. A workover of 42 days was chosen for stage 2 because there were 42 days between the end of stage 2 and the start of stage 3. The average injection rate for stage 3 was 12,585 BBls/day over the 140 days of injection. A standard workover duration of 60 days followed stage 3. The cumulative injected water volume is shown as a function of time in Figure 5-101. The hanging string was located at 25 ft above the cavern bottom for stages 1 and 2 and 14 feet above the bottom for stage 3. The initial OBI was 1142 ft above the cavern bottom for stage 1. The final calculated OBI depth from stage 1 was then used as the starting OBI depth for stage 2. The OBI was 1402 ft above the cavern bottom for stage 3. The evolution of the OBI over time is shown in Figure 5-102. The sharp changes in OBI depth at the end of stage 2 represents a time where the simulated OBI depth at the end of the stage exceeds the measured depth at the beginning of the following stage.

Table 5-55 Summary of Simulation Input for WH111

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2540	4520	1980	25	1142	75749.0	5	60
2	2540	4520	1980	25	--	39597.0	44	42
3	2540	4520	1980	14	1402	12585.0	140	60

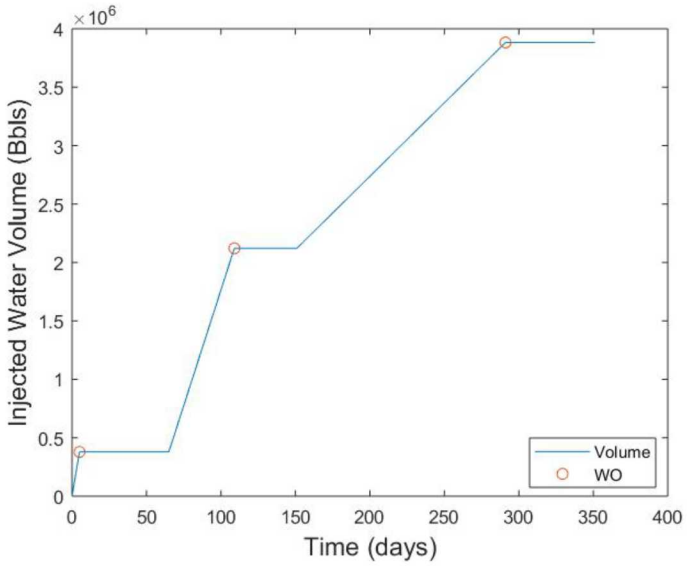

Figure 5-101 Injected water time history for WH111 simulation.

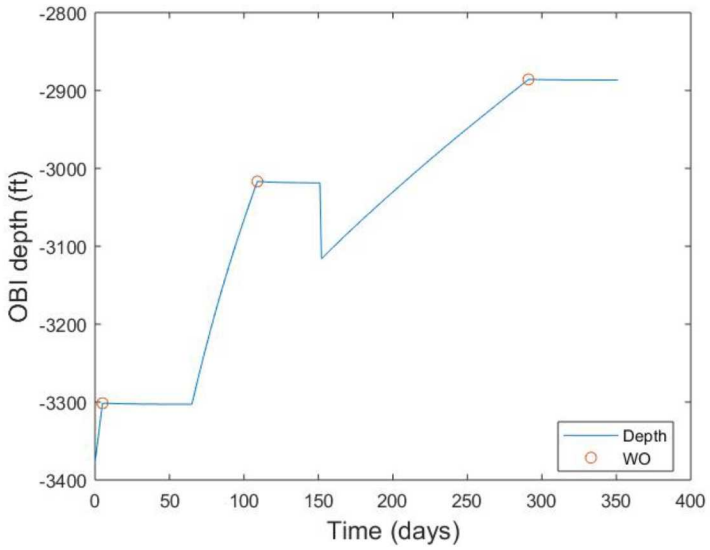

Figure 5-102 OBI depth time history for WH111 simulation.

The outlet specific gravity reached 1.2010, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 3 workover. As summarized in Table 5-56, the total amount of raw water injected was 3.88 MMB creating a volume of 0.63 MMB by leaching over 1603 ft of the cavern wall out to 5 ft.

Table 5-56 Summary of Simulation Output for WH111

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2010	3.88	0.63	1603	5

The simulated cavern shape as a result of the leaching is shown in Figure 5-103. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2015 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-104.

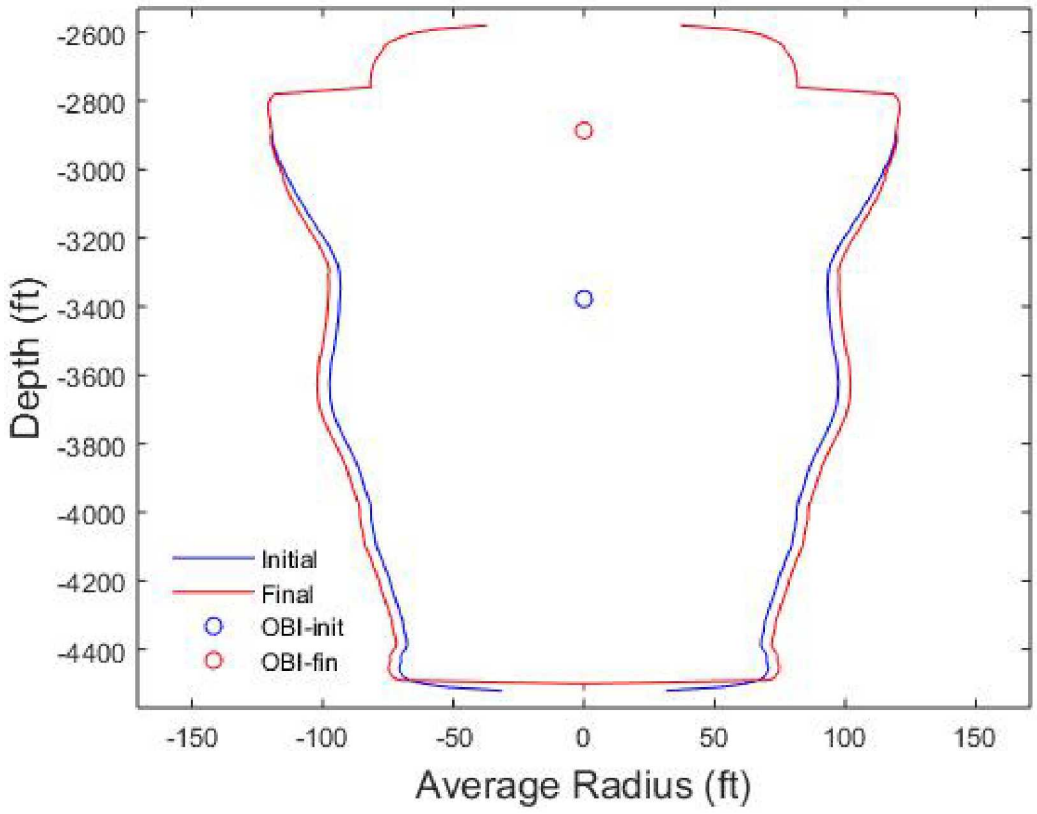

Figure 5-103 Simulated cavern geometry of WH111 with elongated horizontal axis.

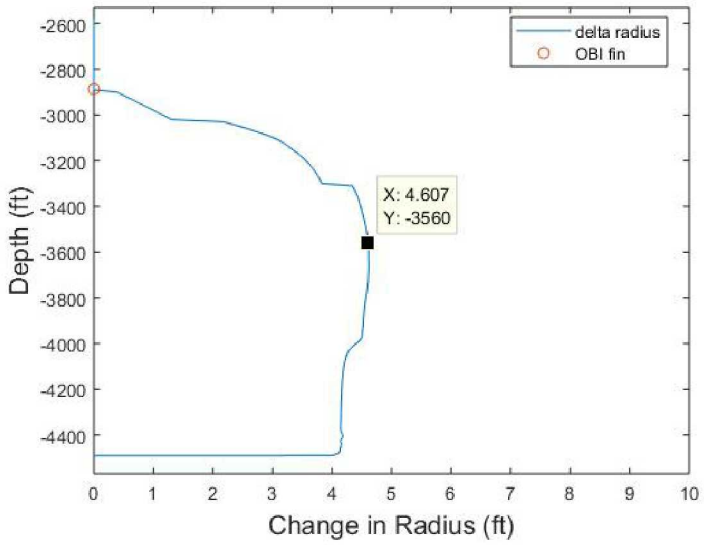

Figure 5-104 Change in radius as a function of depth for WH111.

5.4.5. WH113

WH113 had water movement in 2017 (see Table 4-4) that was modeled in 3 stages summarized in Table 5-57. The average injection rate for the stage was 13,516 BBls/day over the 56 days of injection. A standard workover of 60 days was used to finish all 3 stages. The average injection rate for stage 2 was 43,213 BBls/day over the 4 days of injection. The average injection rate for stage 3 was 1009 BBls/day over the 3 days of injection The cumulative injected water volume is shown as a function of time in Figure 5-105**Error! Reference source not found.**. The hanging string was located at 8 ft above the cavern bottom for all 3 stages. The initial OBI was 42 ft and 194 ft above the cavern bottom for stages 1 and 2, respectively. The final OBI depth for stage 2 was used as the initial OBI depth for stage 3. The evolution of the OBI over time is shown in Figure 5-106.

Table 5-57 Summary of Simulation Input for WH113

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2780	4630	1850	8	42	13516	56	60
2	2780	4630	1850	8	194	43213	4	60
3	2780	4630	1850	8	--	1009	3	60

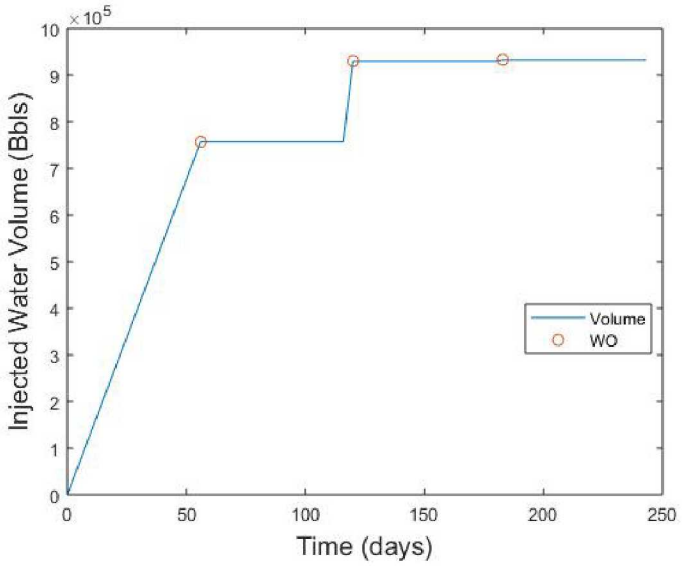

Figure 5-105 Injected water time history for WH113 simulation.

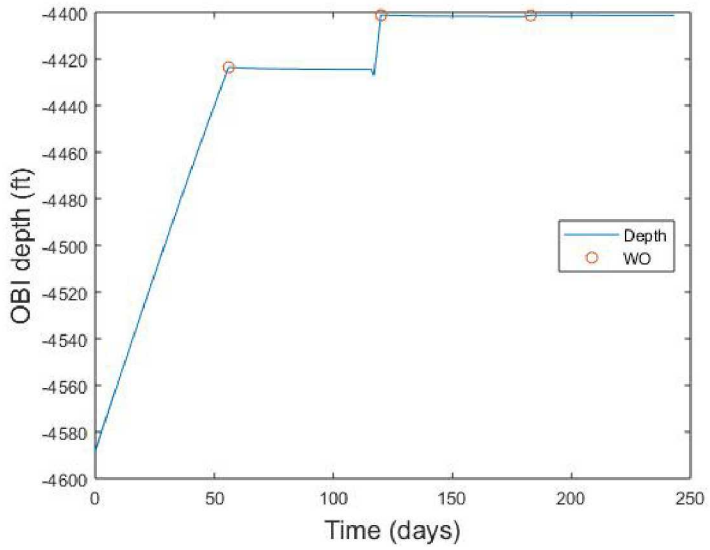

Figure 5-106 OBI depth time history for WH113 simulation.

The outlet specific gravity reached 1.2019, equivalent to the value of 1.2019 expected for salt saturated water, suggesting that leaching was complete at the end of the stage 3 workover. As summarized in Table 5-58, the total amount of raw water injected was 0.93 MMB creating a volume of 0.15 MMB by leaching over 219 ft of the cavern wall out to 11 ft.

Table 5-58 Summary of Simulation Output for WH113

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.2019	0.93	0.15	219	11

The simulated cavern shape as a result of the leaching is shown in Figure 5-107. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2014 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred near the base of the cavern, as shown in Figure 5-108.

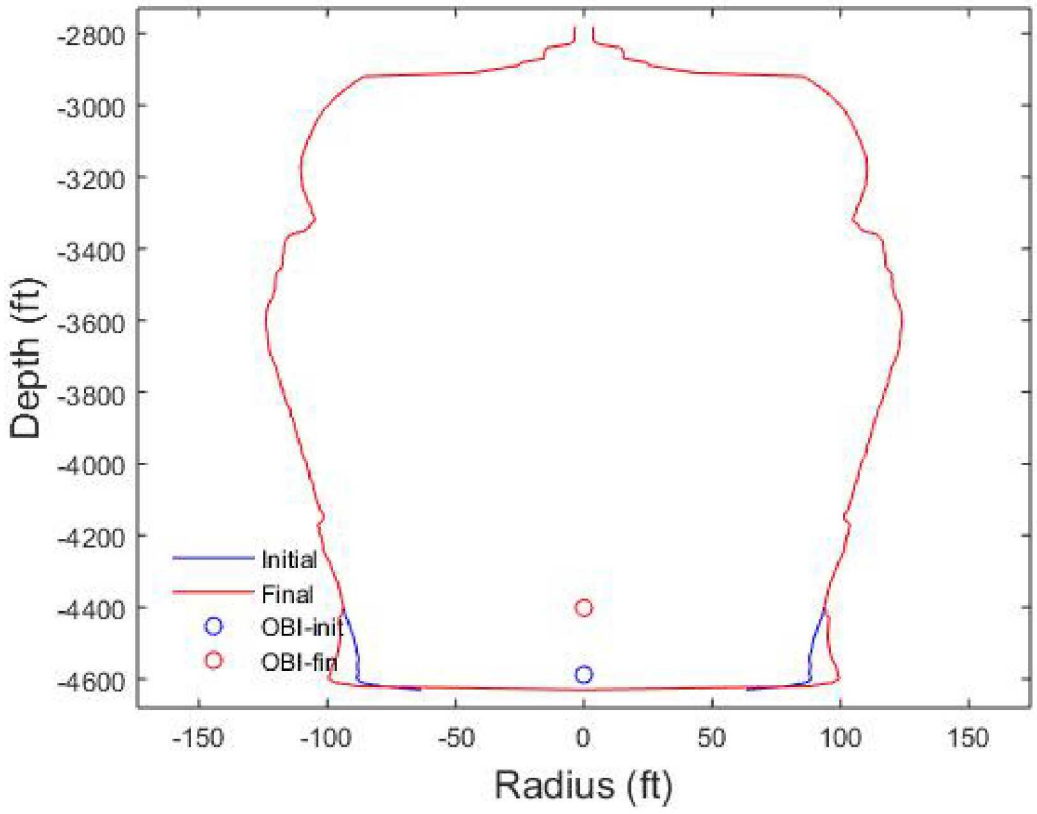

Figure 5-107 Simulated cavern geometry of WH113 with elongated horizontal axis.

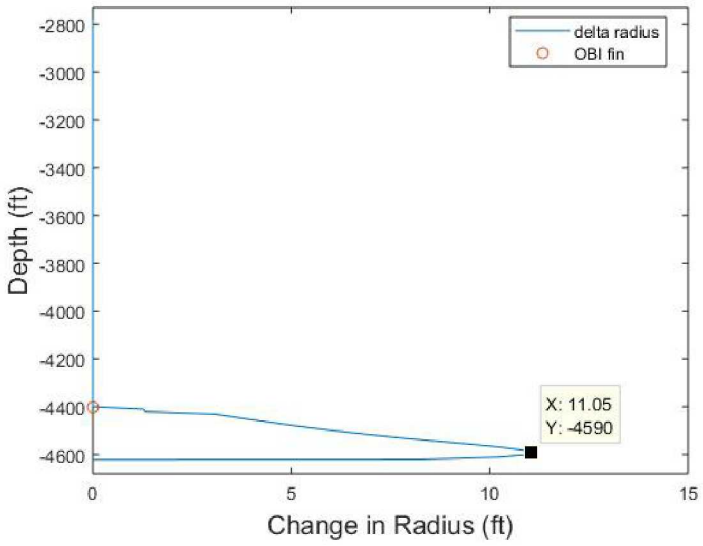

Figure 5-108 Change in radius as a function of depth for WH113.

5.4.6. WH114

WH114 had significant water movement in 2017 (see Table 4-4) in 2 separate stages summarized in Table 5-59. The average injection rate for the first stage was 23,216 BBls/day over the 71 days of injection. The time between the end of injection for the first stage and the start of injection for the second phase was 48 days which was used as the workover duration for stage 1. The average injection rate for the second stage was 9,524 BBls/day over the 134 day injection period. A standard workover duration of 60 days was used at the end of stage 2. The cumulative injected water volume is shown in Figure 5-109. The hanging string was located 30 ft and 323 ft above the cavern bottom for stages 1 and 2, respectively. The initial OBI was 45 ft above the cavern bottom for stage 1 and 346 ft above the cavern bottom for stage 2. The evolution of the OBI over time is shown in Figure 5-110. The sharp change in OBI depth at the end of stage 1 represents a time where the simulated OBI depth at the end of the stage exceeds the measured depth at the beginning of the following stage.

Table 5-59 Summary of Simulation Input for WH114

Stage	Depth of Cavern Top (ft)	Depth of Cavern Bottom (ft)	Cavern Height (ft)	Hanging String Rise (ft)	Oil Brine Interface Rise (ft)	Injection Rate (BBls/day)	Injection Duration (days)	Workover Duration (days)
1	2550	4520	1970	30	45	23216	71	48
2	2550	4520	1970	323	346	9524	134	60

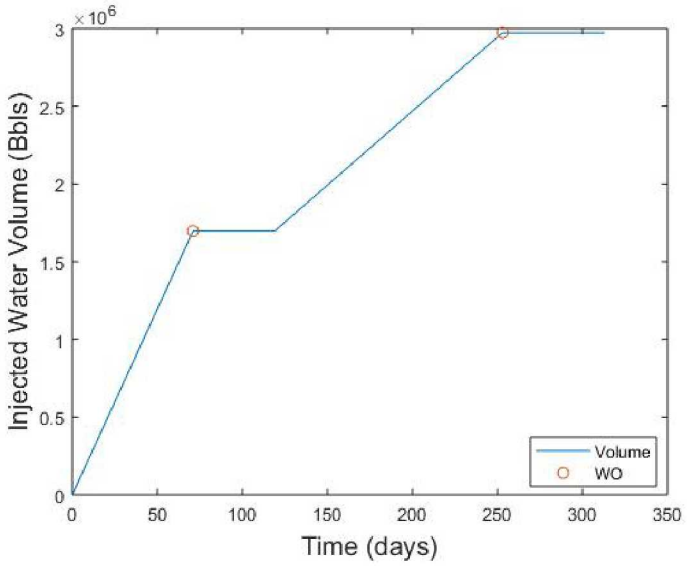

Figure 5-109 Cumulative volume of injected raw water for WH114.

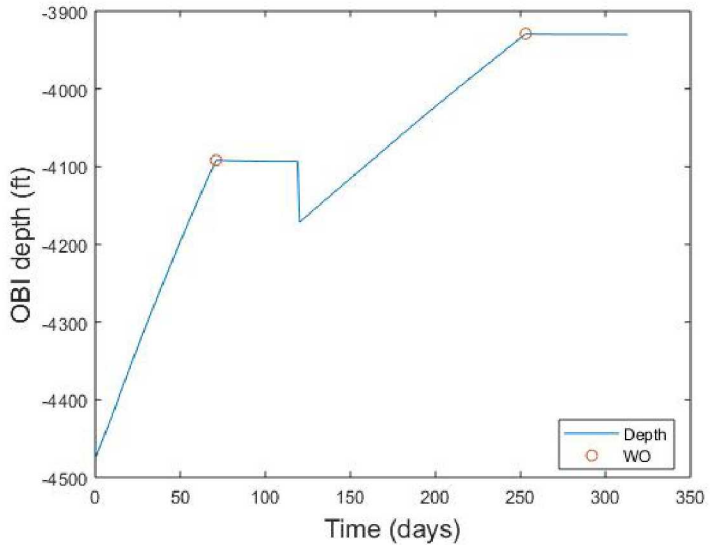

Figure 5-110 OBI depth time history for WH114.

The outlet specific gravity reached 1.1996, close to the value of 1.2019 expected for salt saturated water, suggesting that leaching was near completion at the end of the stage 2 workover. As summarized in Table 5-60, the total amount of raw water injected was 2.90 MMB creating a volume of 0.49 MMB by leaching over 580 ft of the cavern wall out to 17 ft.

Table 5-60 Summary of Simulation Output for WH114

Output Specific Gravity	Injected Water Volume (MMB)	Cavern Volume Created (MMB)	Height Affected (ft)	Max Change in Radius (ft)
1.1996	2.90	0.49	580	17

The simulated cavern shape as a result of the leaching is shown in Figure 5-111. The initial geometry (blue line) is a 2-D axisymmetric representation of the 2015 sonar and the final geometry (red line, final) was calculated with SANSMIC. The initial (blue circle) and final (red circle) OBI positions are also shown. The largest change in cavern radius occurred about 200 ft above at the base of the cavern, as shown in Figure 5-112. The two stage leach with significantly different hanging string and initial OBI depths resulted in a tiered leaching pattern.

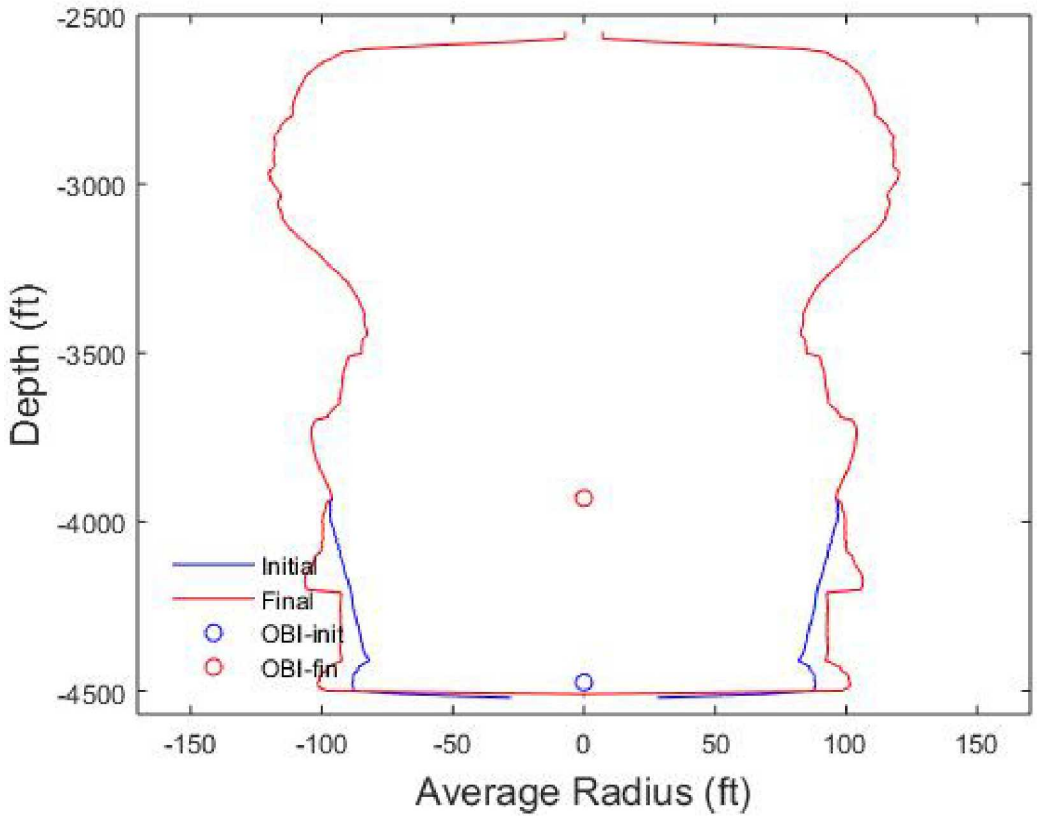

Figure 5-111 Simulated cavern geometry of WH114 with elongated horizontal axis.

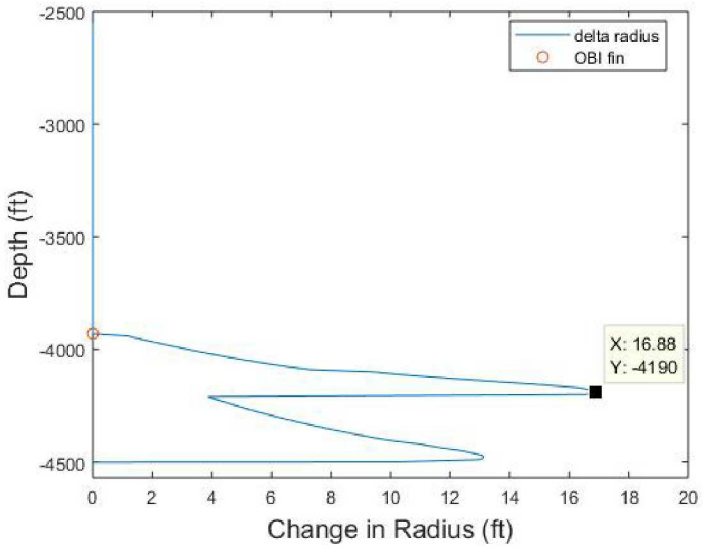

Figure 5-112 Change in radius as a function of depth for WH114.

6. COMPARISON BETWEEN SIMULATED AND MEASURED CAVERN GEOMETRIES

Results from SANSMIC simulations are compared to the current (post-sales) sonars for BH104, BM111 and WH11 in Figure 6-1, Figure 6-2, and Figure 6-3, respectively. In these figures, the starting sonars are shown in green, the 2018 sonar is shown in red, and the SANSMIC prediction is shown in black. It is again noted that the curves listed as sonars in these figures are axisymmetric, equivalent volume representations of the cavern geometry. Without a sonar for comparison at BC, the final simulated position of the BC18 OBI was compared with a measurement of the OBI.

6.1. BH104

SANSMIC results predicted the cavern geometry well for BH104 (see Figure 6-1) with little deviation of the model (black line) from the cavern data (red line) all along the vertical extent of the cavern.

6.2. BM111

SANSMIC results predicted the cavern geometry fairly well for BH111 (see Figure 6-2) with a little underprediction by the model (black line) of the cavern data (red line) between the depths of 3700 ft and 3800 ft.

6.3. WH011

SANSMIC results underpredicted the radial cavern growth for WH011 (see Figure 6-3) by 20 ft with the sonar indicating a radius of 176 ft and SANSMIC predicting a radius of 155 ft. The discrepancy may be related to the fact that in reality the injection rate was not continuous in time as it was modeled in SANSMIC. SANSMIC also predicted the largest radius at a depth of 3710 ft while the sonar indicated the widest radius at 3700 ft.

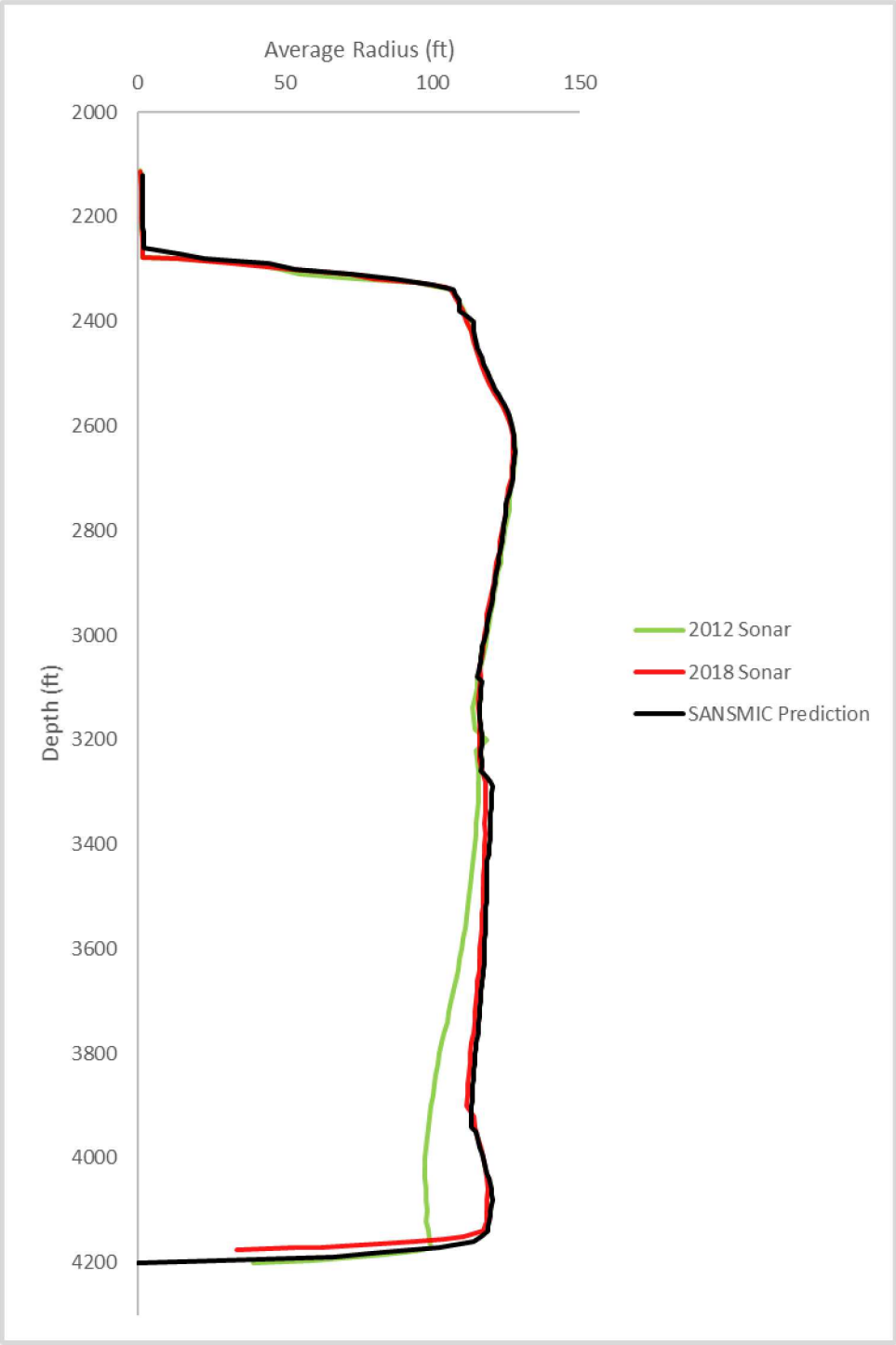

Figure 6-1 Comparison between 2012 sonar (green line), SANSMIC prediction (black line), and 2018 sonar (red line) for cavern BH104.

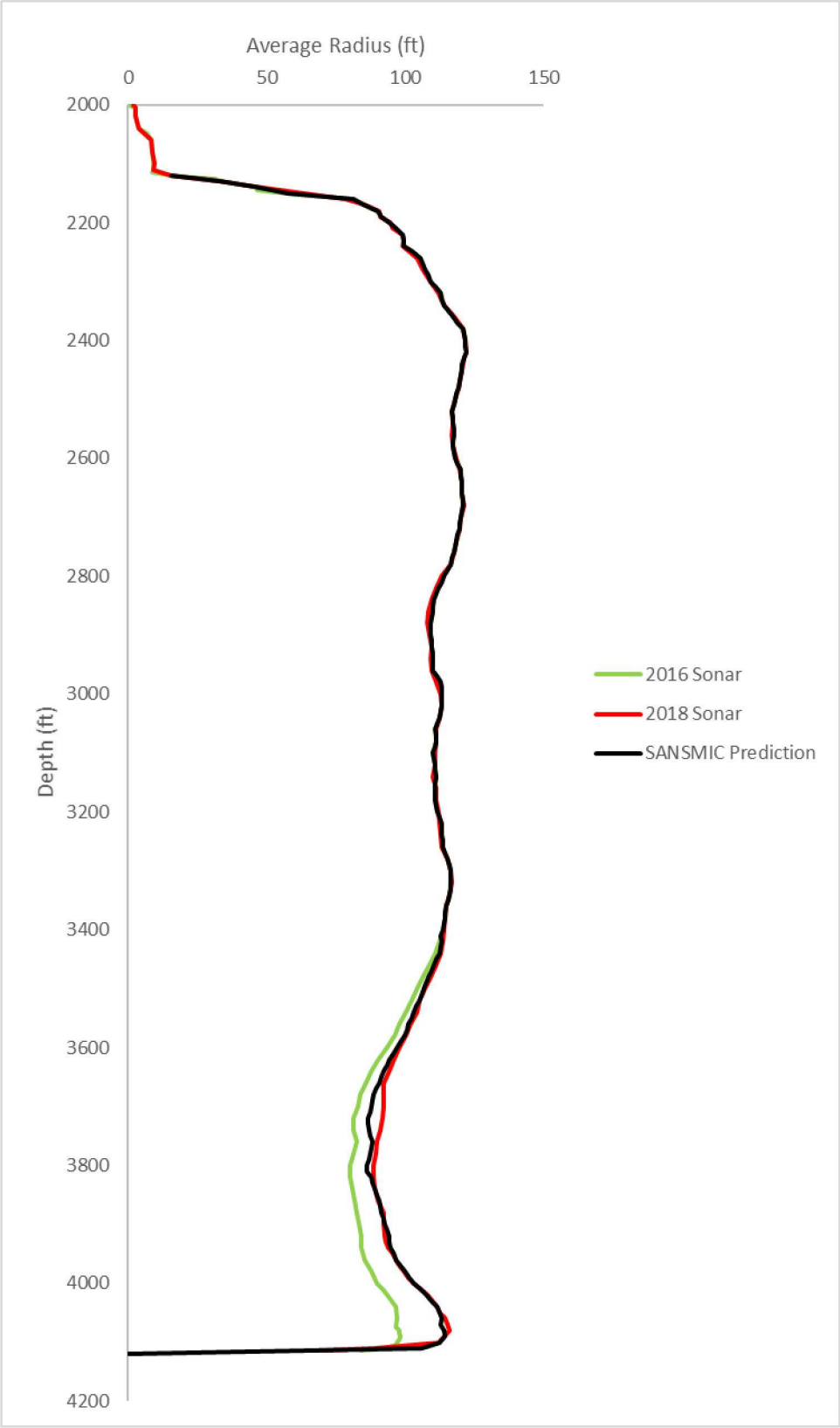

Figure 6-2 Comparison between 2012 sonar (green line), SANSMIC prediction (black line), and 2018 sonar (red line) for cavern BM111.

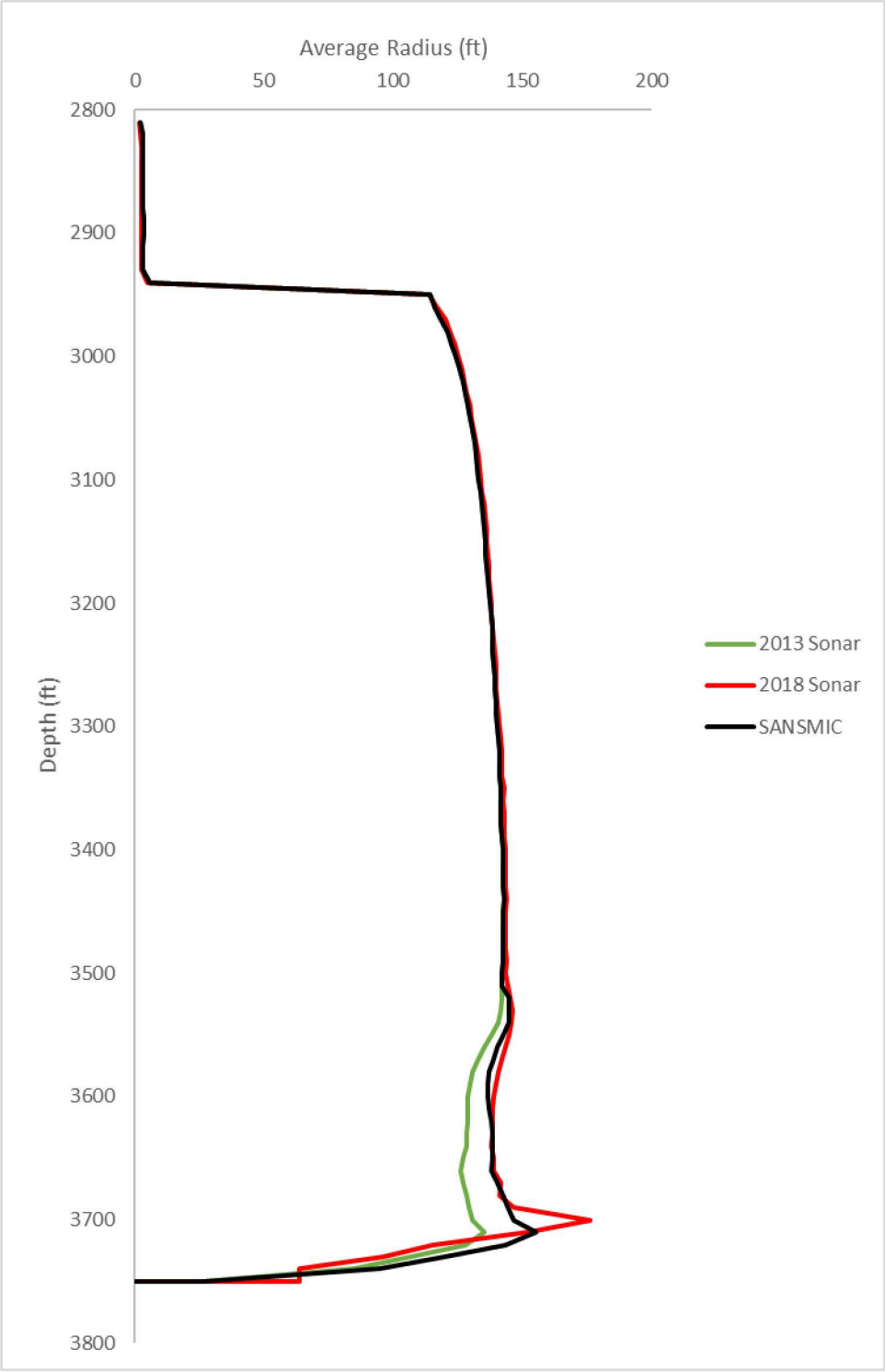

Figure 6-3 Comparison between 2013 sonar (green line), SANSMIC two-stage prediction (black line), and 2018 sonar (red line) for cavern WH011.

6.4. BC18

BC18 has not had a sonar following the recent water movement, however there was an OBI measurement taken on October 6, 2017 after completion of the water movement. That measurement indicated the OBI was 418 ft above the cavern floor which is close to the SANSMIC OBI prediction of 420 ft above the cavern floor.

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