SOLUTION MINING RESEARCH INSTITUTE
679 Plank Road
Clifton Park, NY 12065, USA

Telephone: +1 518-579-6587
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Technical Conference Paper

The Utility of Sonars and the SANSMIC Leaching Code for Monitoring Cavern Shape Development During the Recent Unprecedented Oil Volume Movements at the SPR

Todd R. Zeitler, David B. Hart

Sandia National Laboratories, Albuquerque, New Mexico, United States

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THE UTILITY OF SONARS AND THE SANSMIC LEACHING CODE FOR MONITORING CAVERN SHAPE DEVELOPMENT DURING THE RECENT UNPRECEDENTED OIL VOLUME MOVEMENTS AT THE SPR

Todd R. Zeitler, David B. Hart
Sandia National Laboratories, Albuquerque, New Mexico, United States

Abstract

The Strategic Petroleum Reserve (SPR) has experienced unprecedented oil volume movements over the past few years, including contributions due to sales, exchanges for storage, and Congressional and Presidential drawdowns. The use of raw water injections to remove oil from the SPR caverns results in leaching of the salt cavern walls which leads to the development of additional ullage in these caverns while also changing their shapes. The use of sonars and leaching models to monitor the recent impacts of leaching across caverns at all four SPR sites is the focus of this paper.

The use of sonars provides the most direct measure of cavern shape and growth but comes with some limitations. The sonars used at the SPR sites produce three-dimensional representations of the caverns primarily based on 10-20 ft vertical resolution and a ~1-3% uncertainty on horizontal measurements. Sonars are typically performed on SPR caverns every 5-10 years by state regulations. However, with the increased extent of leaching taking place in SPR caverns, an increased number of sonars have been performed as a monitoring step. For caverns where recent sonars are not available and substantial raw water injections have occurred, modeling of the cavern development due to leaching has proved to be a useful monitoring tool.

The Sandia Solution Mining Code (SANSMIC) has been used to predict cavern leaching in SPR caverns using standard salt dissolution models that account for the salinity of the injected water. Simulations use sonar-derived cavern shapes and raw water injection histories to project cavern growth. The results derived from this modeling tool are shown to be in good general agreement with sonar data. However, the SANSMIC code has its own limitations with respect to predicting cavern shapes, such as the need for an axisymmetric (rather than full 360°) cavern representation, inheritance of the uncertainty inherent in the sonars, and lack of process models for creep and floor rise.

The utility of sonars and the SANSMIC tool for monitoring cavern shape development during the recent unprecedented oil volume movements at the SPR will be shown via recent examples where partial and full drawdowns of SPR caverns have occurred.

Keywords: leaching, salt dissolution, model uncertainty, sonar

Introduction

The U.S. Strategic Petroleum Reserve (SPR) is a crude oil storage system run by the U.S. Department of Energy (DOE). The reserve consists of 60 active storage caverns spread across four sites near the Gulf of Mexico. The Big Hill (BH) and Bryan Mound (BM) sites are located in Texas, and the Bayou Choctaw (BC) and West Hackberry (WH) sites are located in Louisiana.

The purpose of the SPR, as it was designed, is to mitigate emergency supply disruption of crude oil within the U.S. and to also fulfill International Energy Agency treaty obligations. Because of the large size of the reserve, brine drive has never been a part of the SPR; instead, oil is withdrawn – or drawn down – using "raw" water. Raw water is local surface water that is fresh to saline in its salt content, highly undersaturated when compared to (fully saturated) brine, and readily available at rates necessary to support drawdown.

As such, raw water injection reduces the salinity of the brine in the cavern below the oil. The now-undersaturated brine in contact with the cavern walls dissolves the salt at the cavern walls, and this process constitutes cavern leaching.

Sonars provide important information about cavern geometry, but when recent sonar data is not available and substantial raw water has been injected since the last sonar, computational modeling of the leaching that has occurred provides insight into developing cavern geometry. Leaching effects are modeled with the Sandia Solution Mining Code (SANSMIC) [1]. 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 salinity of the injected water, temperature, and flow velocity [1].

Problem

Unprecedented oil volumes have been drawn down from the SPR in recent years (Figure 1). Leaching effects across all four SPR sites have been documented in annual reports for raw water injections in calendar years 2017 through 2021 [2][3][4][5]. The reports show predictions of cavern geometry development due to raw water injections and, where possible, comparisons of the modeling to follow-up sonars are made. Those annual reports also provide additional background information on the use of SANSMIC for leaching at the SPR.

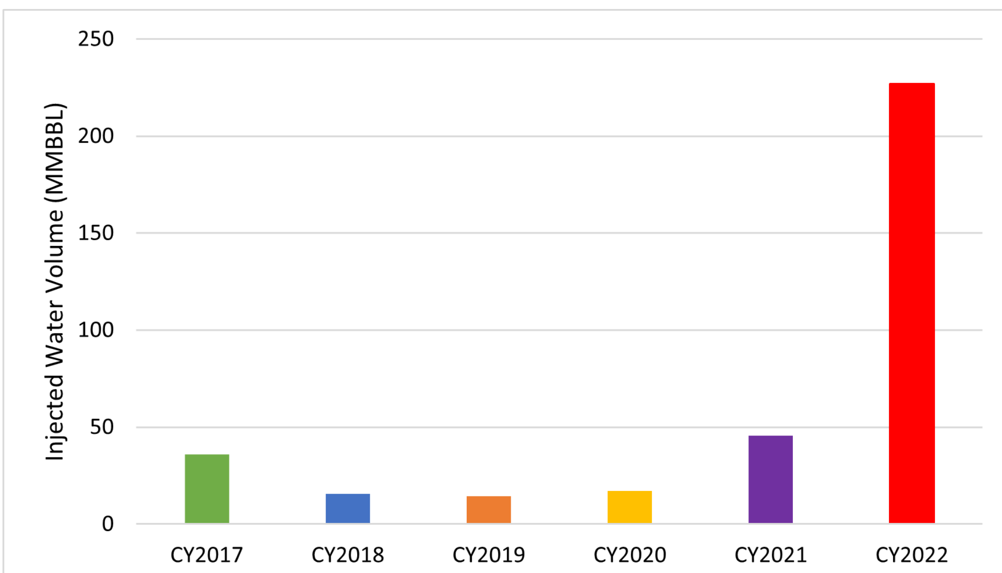

Figure 1. Raw water injection volumes across the SPR in recent calendar years (CY).

With the increased drawdowns comes increased use of leaching modeling and sonars to track the development of cavern geometry. The underlying uncertainties in downhole sonar measurements and raw water injection volumes play roles in leaching modeling predictions, but to-date, the extent of the impacts of these uncertainties has not been investigated. Understanding the potential impacts of these two sources of uncertainty will increase confidence in use of the SANSMIC tool in the short term and provides guidance for planned software updates in the long term.

Cavern Leaching Behavior Following Raw Water Injection

To remove oil from the SPR, oil is withdrawn using water displacement where water is injected into the bottom of the cavern using a brine string pushing oil out of it (Figure 2). “Raw” drive water for SPR is obtained from naturally occurring surface water near the sites and is not saturated with brine. As such, raw water injection reduces the salinity of the brine in the cavern below the oil. The now-undersaturated brine in contact with the cavern walls dissolves the salt at the cavern walls, and this process constitutes cavern leaching.

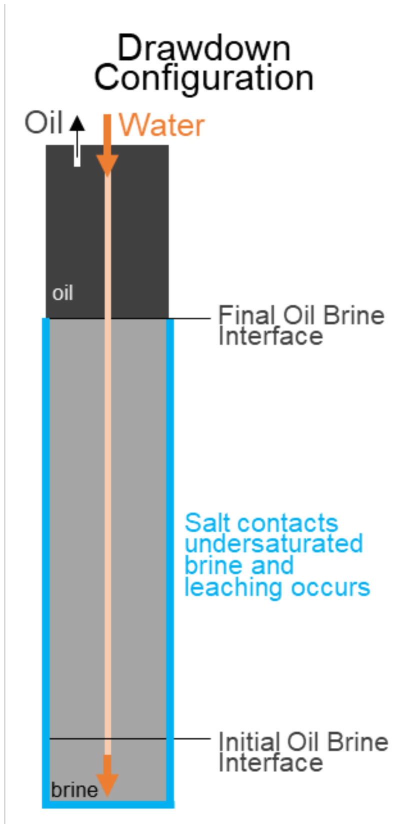

Figure 2. Schematic of drawdown configuration which results in cavern wall leaching [5].

The impact of leaching on cavern shape depends on the type of leaching that occurs. Oil sales generally involve partial drawdowns of the oil inventory in several caverns. The leaching pattern for a single-phase partial drawdown generally involves a “flare” pattern with the greatest growth at the depth of the end of the brine string tubing (EOT) that tapers up to the final oil-brine interface (OBI) depth **(**Figure 3**)**. This pattern reflects the concentration of salt in the injected water over time, as the well-mixed brine in the region between the EOT and OBI is lower in concentration compared to the rest of the cavern brine—with greater exposure times to undersaturated brine near the EOT, there is a resultant greater radial growth.

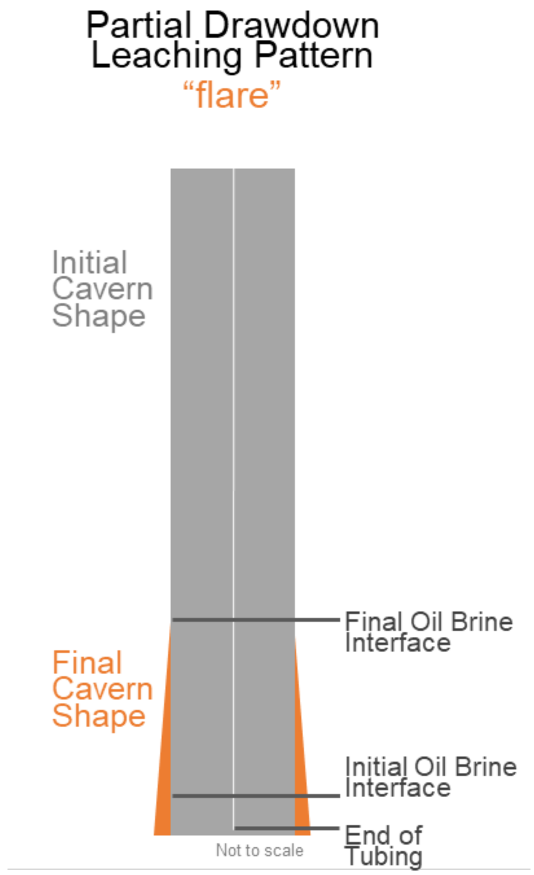

Figure 3. Schematic of leaching pattern from a partial drawdown [5].

Many SPR caverns have had multiple phases of leaching and the final leaching pattern depends on the cumulative effects for all phases. Caverns with multiple leaching phases have a range of leaching outcomes which deviate from the single-phase flare pattern and are difficult to predict a priori from any single metric. Thus, SANSMIC modeling has proved to be particularly helpful in understanding the potential leaching outcomes for these caverns.

Modeling Cavern Leaching Using SANSMIC, the Sandia Solution Mining Code

Leaching effects are modeled with the Sandia Solution Mining Code (SANSMIC) [1]. 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 salinity of the injected water, temperature, and flow velocity [1]. Simulations use sonar derived cavern shapes at the start of the simulation, the actual casing depths, and the field-reported injected water volumes. The model computes the effects of leaching on cavern shape and volume, treating the cavern as a stack of cylindrical disks and limiting leaching to cavern depths below the OBI. The OBI moves as fluids are moved into the cavern.

SANSMIC simulations start from a known cavern geometry, EOT and OBI 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. This limitation of the code becomes more important for irregularly shaped caverns. The results of the sonar survey are typically provided with 10-20 ft (3-6 m) vertical resolution. The grid cell resolution in the SANSMIC simulations is downscaled to 1 ft (0.3 m) via interpolation of the sonar data.

The EOT and OBI depths are taken from the weekly site reports generated by the SPR, which take into account the most recent data on the depth of the brine string, as well as fluid movements since the last OBI measurement. The daily raw water injection amounts are taken from the SPR CAVEMAN database. For each phase (period of injection time), an average injection rate is calculated from the daily rates over the injection duration (usually many days). This approach is illustrated in Figure 4.

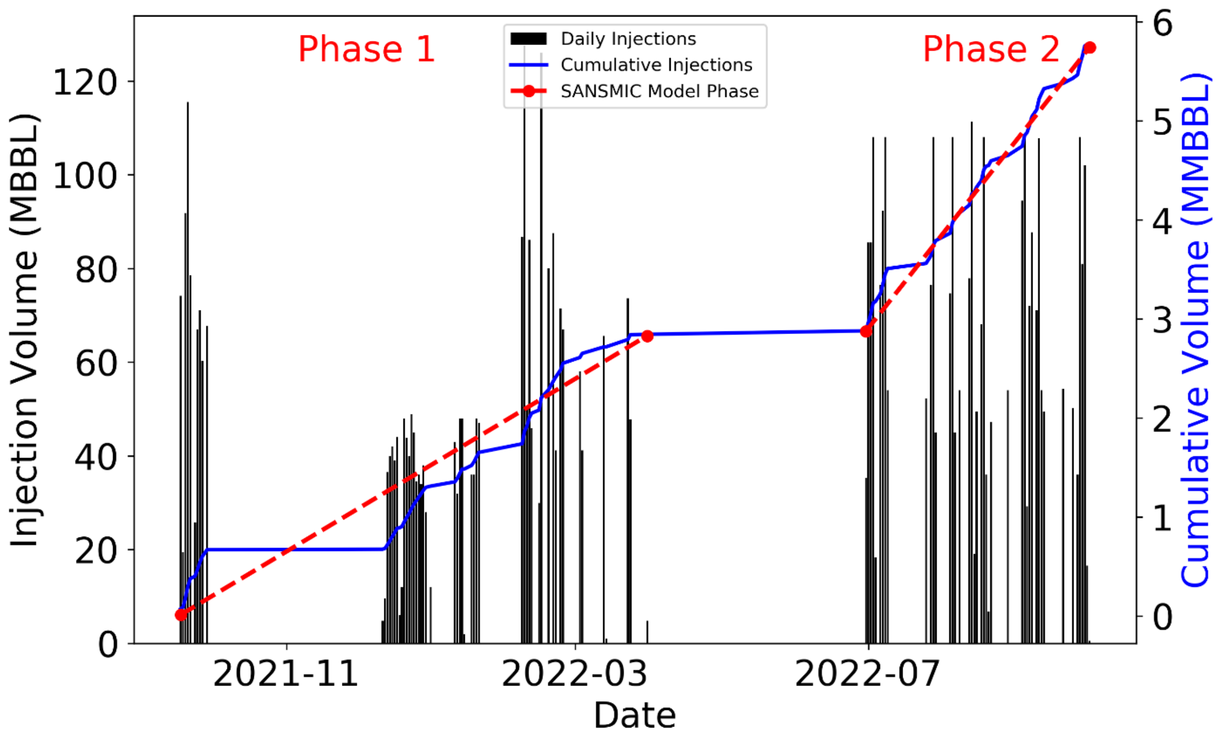

Figure 4. Example of fluid movements and modeled phases for leaching in a cavern with two distinct injection periods.

Addressing Uncertainty in Cavern Leaching Calculations

SANSMIC was validated for conventional leach (both direct and reverse) capabilities by comparison with cavern creation data [6]. Subsequent comparisons between SANSMIC modeled cavern geometries and sonar measurements following the 2011 oil sale indicated the simulated cavern radius is within 5% of the measured cavern radius and the leached volumes are within 10% [7]. A re-validation of SANSMIC in withdrawal, direct and reverse leach modes for caverns leached by SPR indicated that simulated radial profiles match sonar observations within 1.5% - 12% and the observed leach volume was simulated within 1% -13% [8].

Based on discussions with sonar vendors, Sandia has used an assumed volumetric accuracy for a single sonar survey of ±1% to ±3% of the volume, depending on the complexity and size of the cavern; recent uses of sonar data when comparing fluid movements to the sonar-calculated volume change have seemed to show an uncertainty of ±3% to ±5% is appropriate for use with changes in cavern volume (slightly higher than twice the maximum single-sonar volume uncertainty). With older sonar surveys, irregularly shaped caverns, and with very wide caverns, the error bounds may increase. One of the sources of uncertainty arises from the speed-of-sound assumed in each fluid (brine or oil), which directly impacts the calculated distance between the sonar tool and cavern wall. Additional uncertainty may be attributed to the limited number of data points taken radially (typically at 5° increments) which allow for the possibility of missing irregularities in the cavern geometry.

There is also uncertainty associated with the raw water injection volumes documented in the SPR CAVEMAN database. Injection volumes come from valve meters. Daily injection volumes are input manually into CAVEMAN for each cavern during drawdown injection periods. The maximum uncertainty in fluid volumes is estimated to be about 3% due to transcription and meter errors and would be at least ±1% using automated readings (based on meter accuracy limits).

Impacts of Uncertainty on Hypothetical Cylindrical Caverns with Idealized Fluid Injection Rates

In this section, we analyze the impacts of uncertainties associated with raw water volumes and sonar surveys on hypothetical, cylindrical caverns with idealized fluid injection rates in order to clearly see the trends in impacts across varied cavern radii. In the next section, the impacts of uncertainty are analyzed for two SPR caverns with real raw water injection histories.

Hypothetical caverns with a height of 2000 ft (600 m) of nominal radii 100, 150, 200, and 250 ft (30, 46, 61, and 76 m) were investigated with nominally 10 MMB (1.6 MM m^3) injected over 100 days. The brine string end of tubing (EOT) was set to 30 ft (9 m) above the cavern floor and the oil-brine interface (OBI) was set to 50 ft (15 m) above the cavern floor.

Figure 5 shows the results for a 100 ft (30 m) radius cavern when subject to ±3% uncertainty on the injection volume (left) and ±3% on the sonar survey (right). The impact of injection volume is relatively small compared to the impact of the sonar survey for the same level of uncertainty. This is consistent with the model inputs, as the uncertainty for the volume is tempered by the ~15% leaching rate observed in SANSMIC simulations and SPR cavern growth.

For example, a 3% uncertainty on 10 MMB (1.6 MM m^3) is 300 MB (48 M m^3), which would result in only 45 MB (7 M m^3) of cavern growth due to the 15% leaching rate. Spread over 1000 ft (300 m) vertically in the cavern growth zone, that would be only about 0.4 ft (0.1 m) of additional growth on average due to leaching. Because the uncertainty is on the volume, the resulting impact on cavern is not linear, but proportional to the cross-sectional area (no uncertainty in the height is assumed) or proportional to the square of the cavern radius. Thus, the impact on cavern radius due to the uncertainty in injection volume is relatively small. That the SANSMIC calculations bear this out is encouraging and gives confidence in the modeled results.

On the other hand, the sonar uncertainty is applied directly to the cavern radius, as the sonar survey measurement is the distance from the sonar tool (near the center of the cavern) to the cavern wall. As a result, the ±3% uncertainty applied here directly impacts the cavern radius. This is evident in the wide range of resultant cavern radii in the right side of Figure 5.

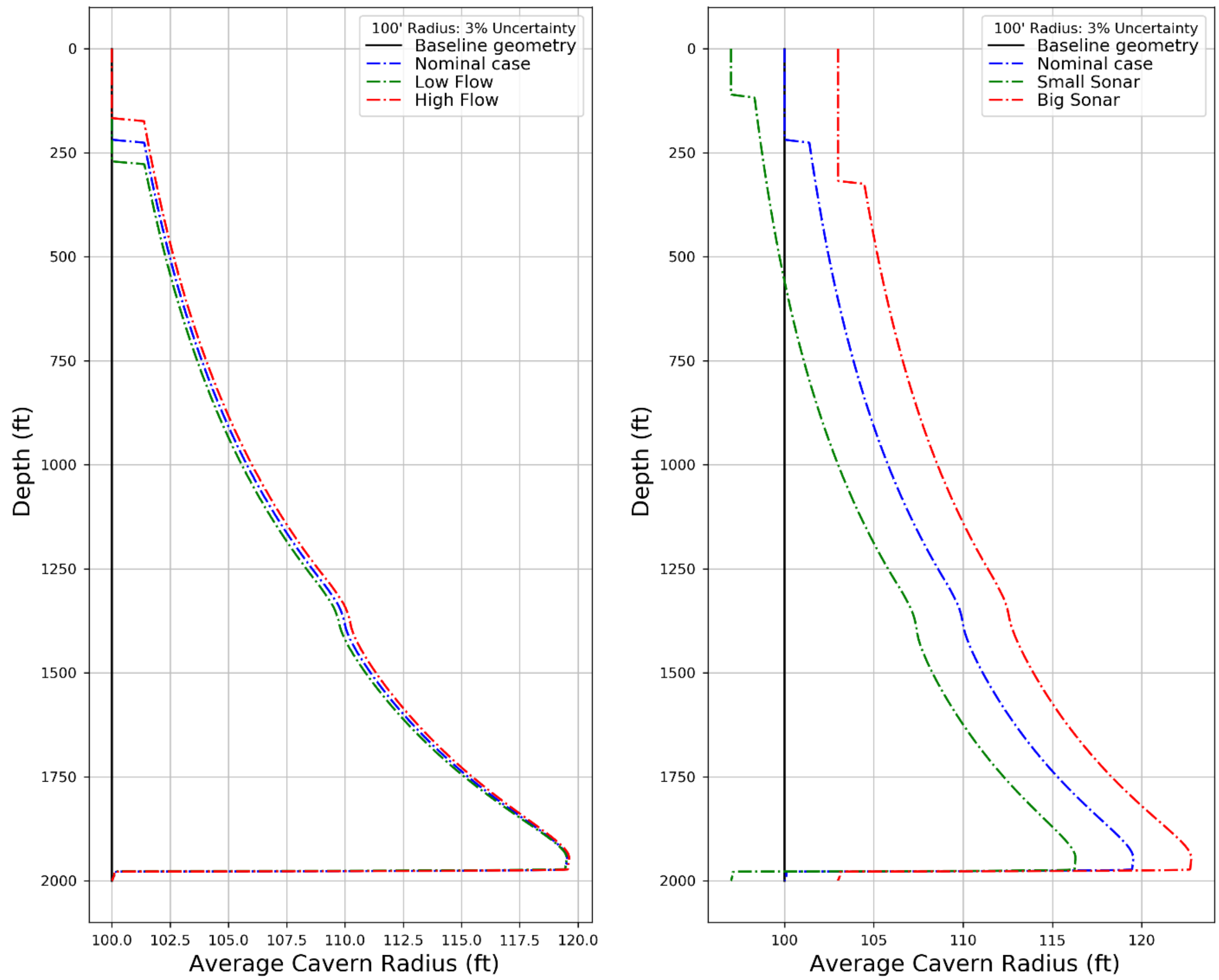

Figure 5. Results of SANSMIC modeling for 10 MMB (1.6 MM m^3) of raw water injected into a cavern of radius 100 ft (30 m). Results when the injection volume is subject to ±3% uncertainty (left) and when the sonar survey is subject to ±3% uncertainty (right).

To investigate the potential combined impacts of uncertainties due to injection volume and sonar survey, all combinations of “low”/”high” injection volumes and “small”/”big” sonars for a ±3% uncertainty were calculated. Final results are shown in Figure 6, where there are three groups of results observed. Each group is associated with changes due to initial cavern radius (i.e., uncertainty in sonar survey) and the small variations within each group are due to changes in injection rate (i.e., uncertainty in injection volume). Again, it is clear that the sonar uncertainty is driving the overall variation in observed potential cavern geometries, while the injection volume uncertainty is relatively minor (for the same level of uncertainty).

Figure 7 shows the minimum and maximum differences from the initial cavern radius (100 ft, 30 m), as well as the range of radii, as a function of depth for the combinations of uncertainties represented in Figure 6. The values range from 5 to 7% in the cavern growth zone, which is largely driven by the ±3% uncertainty in sonar survey. For the 100 ft (30 m) cavern represented here, that would translate to ±3 ft (±0.9 m) uncertainty in the location of the cavern wall.

Note that the increased growth near the cavern floor is expected, as the well-mixed brine in the region between the EOT and OBI is higher in concentration compared to the rest of the cavern brine—with greater exposure times to undersaturated brine near the EOT (which is close to the cavern floor), there is a resultant greater radial growth. The growth patterns for the minimum and maximum cases are similar, but not identical, but that is also expected; the decreased radius in the "minimum" case results in cavern with less cavern wall surface area and thus leads to a smaller cavern growth volume, especially near the cavern floor where the difference grows with time due to increased raw water volumes. As a result, the range of values exceeds 6% in that region. Higher up in the cavern around a depth of about 300 ft (90 m), there is a discrepancy observed in which it appears as though the percent change drops to about 4%; this is expected and is due to the OBI of the smaller cavern being higher up than for the larger cavern. Again, the consistencies between the SANSMIC results and expected impacts gives confidence in the code and underlying models.

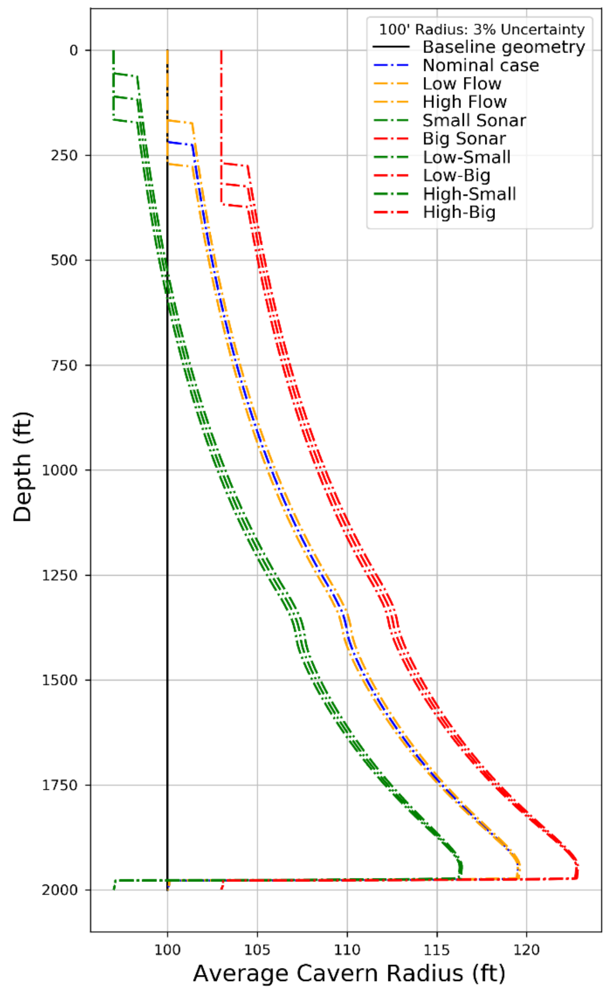

Figure 6. Results of SANSMIC modeling for 10 MMB (1.6 MM m^3) of raw water injected into a cavern of radius 100 ft (30 m). Results for combined uncertainties when the injection volume and sonar surveys are each subject to ±3% uncertainty. Low/High refers to -3/+3% uncertainty applied to injection volume. Small/Big refers to -3/+3% uncertainty applied to sonar survey.

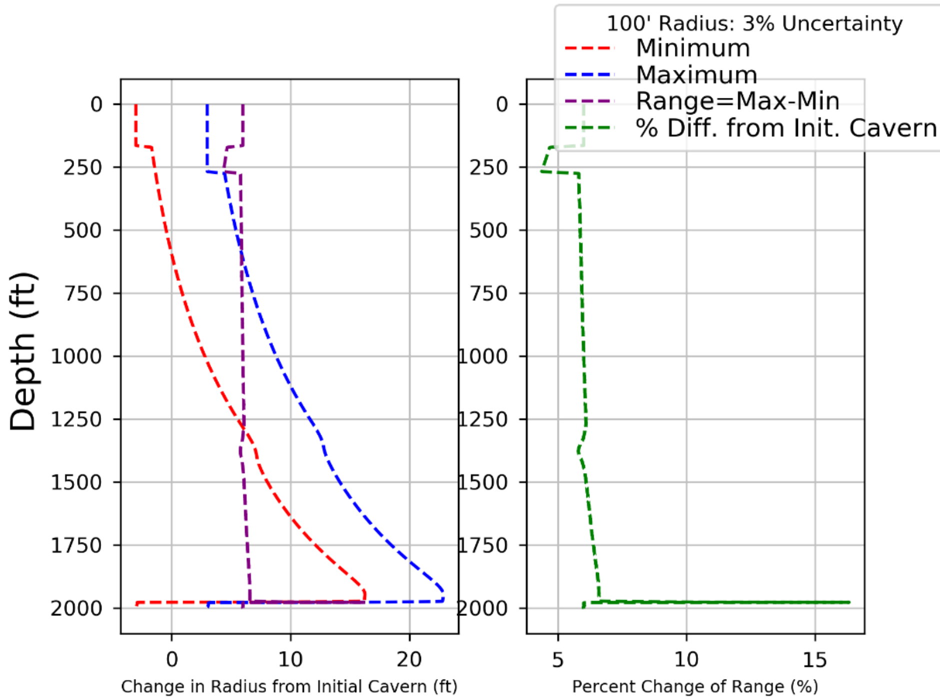

Figure 7. Minimum and maximum differences from the original geometry for the 100 ft (30 m) radius simulations with combinations of uncertainty shown in Figure 6. The range of resultant radii at each depth is also shown in feet (left) and as percentage of the original cavern radius (right).

An additional set of runs of the 100 ft (30 m) radius model was performed with ±3% uncertainty on the injection volumes and the more typical (though perhaps not bounding) ±1% uncertainty on the sonar survey. Results are shown in Figure 8 for a sonar survey subject to ±1% uncertainty (left) and the combined impact of ±3% uncertainty on the injection volume and ±1% uncertainty on sonar survey.

Figure 9 shows the minimum and maximum differences from the initial cavern radius (100 ft, 30 m), as well as the range of radii, as a function of depth for the combinations of uncertainties represented in Figure 8. The range of values is in the range 2-3% in the cavern growth zone, which is largely driven by the ±1% uncertainty in sonar survey. For the 100 ft (30 m) cavern represented here, that would translate to ±1.5 ft (±0.5 m) uncertainty in the location of the cavern wall. Note that the apparently large change at the cavern bottom is not significant and is due to growth differences for single grid cell at the end of the injection plume below the EOT.

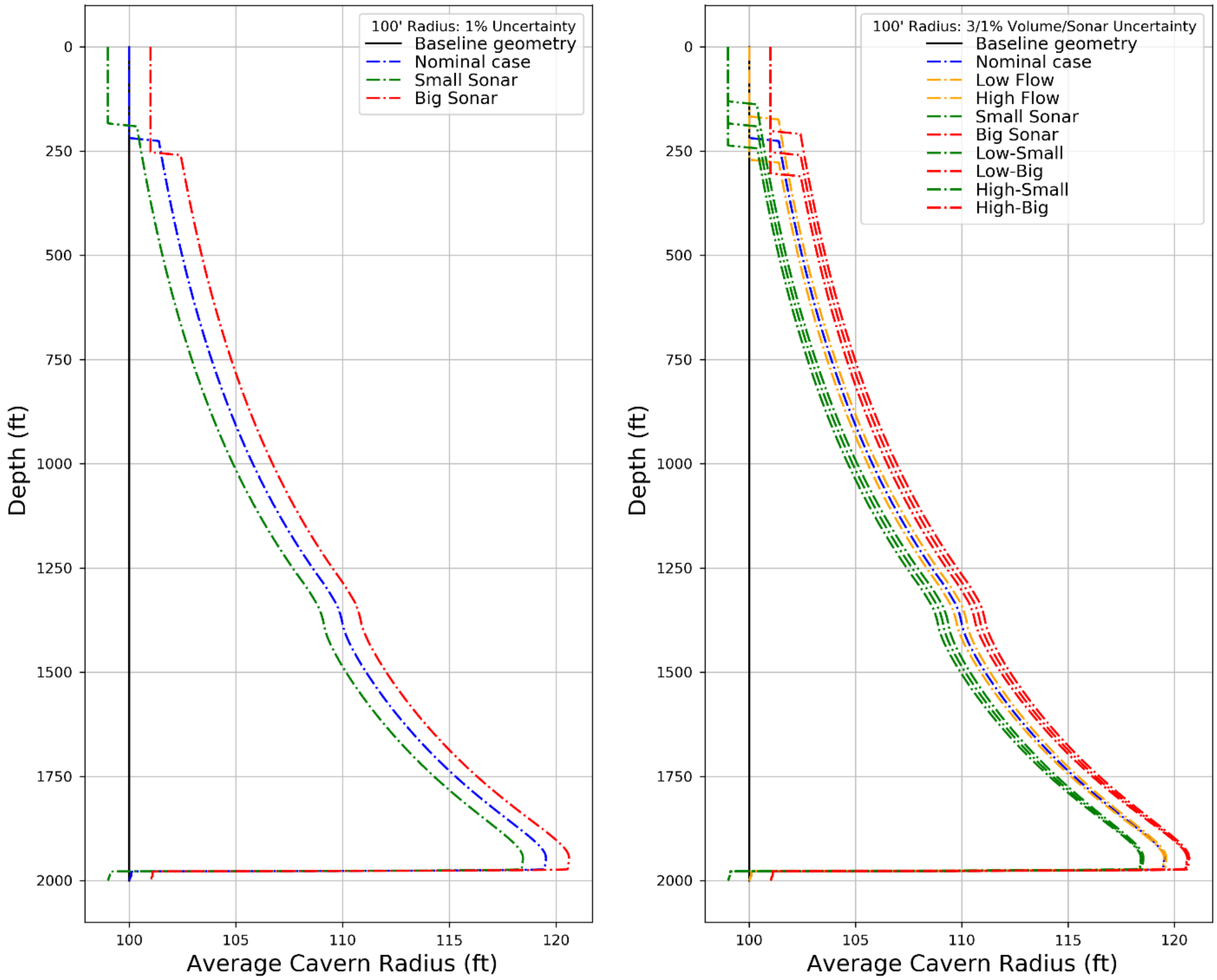

Figure 8. Results of SANSMIC modeling for 10 MMB (1.6 MM m^3) of raw water injected into a cavern of radius 100 ft (30 m). Results when the sonar survey is subject to ±1% uncertainty (left) and when the injection volume is subject to ±3% uncertainty and the sonar survey is subject to ±1% uncertainty (right). Low/High refers to -3/+3% uncertainty applied to injection volume. Small/Big refers to -1/+1% uncertainty applied to sonar survey.

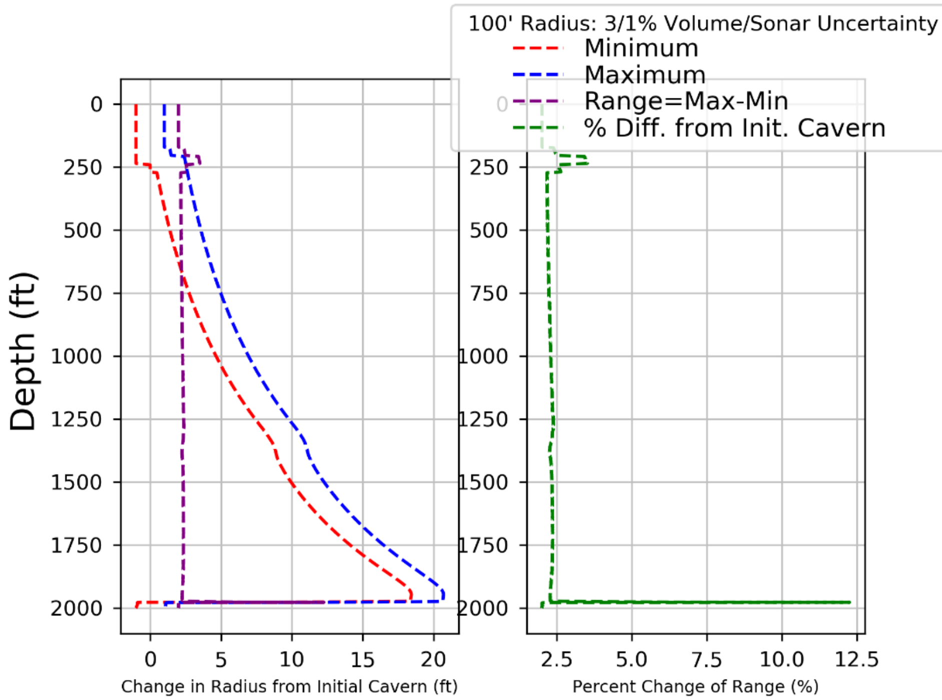

Figure 9. Minimum and maximum differences from the original geometry for the 100 ft (30 m) radius simulations with combinations of uncertainty shown in Figure 8 (right) (±3% for injected volume and ±1% for sonar survey). The range of resultant radii at each depth is also shown in feet (left) and as percentage of the original cavern radius (right).

The investigation was extended to caverns with radii up to 250 ft (76 m) for uncertainties ranging from ±1 to ±10% for both raw water injection volume and sonar survey. The results were consistent with expectations, as the sonar uncertainty drives the overall observed differences in resultant cavern geometries. In other words, the range of output cavern geometries is only slightly impacted by the injection volumes. Figure 10 summarizes the results across all cavern radii and uncertainty levels. Trends are generally linear due to the linear relationship between the sonar uncertainty and cavern radius. The range of values are generally consistent with expectations for an uncertainty driven by sonar survey. For example, at the ±5% uncertainty level, the full range would be expected to be 10 ft (3 m) for a 100 ft (30 m) cavern radius and 20 ft (6 m) for a 200 ft (60 m) cavern radius). The observed maximum ranges are slightly higher due to the leaching process itself near the cavern floor (see the right side of Figure 7 and discussion above).

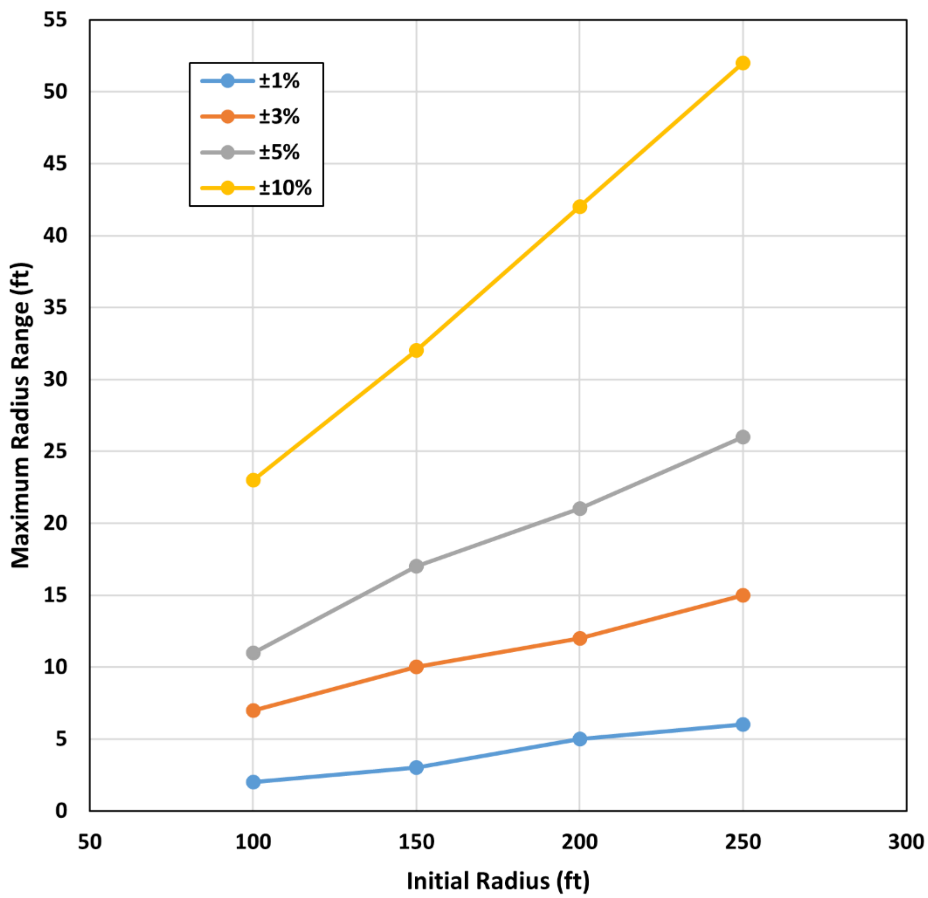

Figure 10. Summarized results (maximum range in output radii) for SANSMIC simulations covering cavern of radii 100-250 ft (30-76 m) and uncertainty levels ±1 to ±10%.

Impacts of Uncertainty on Two SPR Caverns with Real Fluid Injection Histories

The investigation was extended to two SPR caverns with recent drawdowns, Bayou Choctaw 18 (BC-18) and Big Hill 109 (BH-109). Each cavern also had a follow-up sonar following drawdown, which allows for comparison of SANSMIC modeling results with sonar measurements.

The BC-18 cavern had a sonar in 2020 which provided the baseline cavern geometry. The injection history for BC-18 consisted of injections in 2021 and 2022 totaling over 10 MMB (1.6 MM m^3). For the purposes of SANSMIC modeling, these injections were divided into four phases, each with a different injection rate applied to result in the same total injection volume over all four phases (Figure 11). This is consistent with the methodology used in our typical leaching analyses [5].

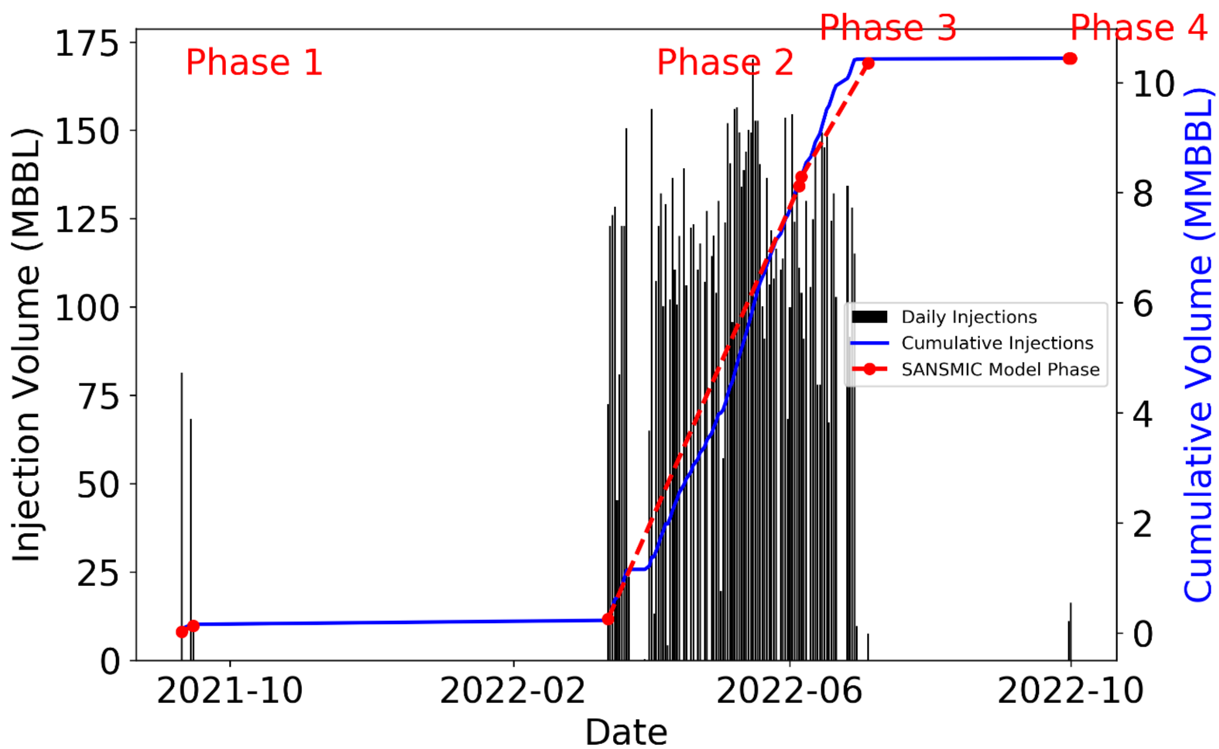

Figure 11. Raw water injection history for BC-18 between 2020 and 2022 sonars.

An identical simulation methodology was applied to BC-18 as was applied to the hypothetical, cylindrical caverns above. Injection rates were scaled up or down for various levels of uncertainty and the sonar survey geometries were also adjusted by the same levels of uncertainty. Combinations of the two uncertainty types were applied to additional simulations as above. The resultant geometries (minimum and maximum radii at each depth) are shown in Figure 12 for ±3 and ±5 levels of uncertainty. The original and final sonars are also shown for comparison.

In the growth region (depths of ~2500-3900 ft, 760-1200 m), SANSMIC-predicted growth is similar in shape and extent to the resultant growth shown by the 2022 sonar. Results are generally within the bounds of the ±3% uncertainty, but in some cases are not bounded until the ±5% level. Near the prominent feature at about 3000 ft (910 m), even the 5% level of uncertainty in SANSMIC results does not exceed the 2022 sonar measurements.

This highlights a limitation of the SANSMIC code: near abrupt changes in cavern geometry slope, particularly when the slope is near horizontal, we often do not see good agreement with sonar measurements. This is due in part to the SANSMIC leaching model which currently only supports radial leaching and not vertical leaching. So, while the prominent feature (at least on axisymmetric average) may have been largely reduced due to the high horizontal surface area, the SANSMIC model underpredicts the extent of leaching in this area. Future versions of the SANSMIC code may be able to address this limitation when a move is made from axisymmetric cavern geometry representations to full 3-D representations.

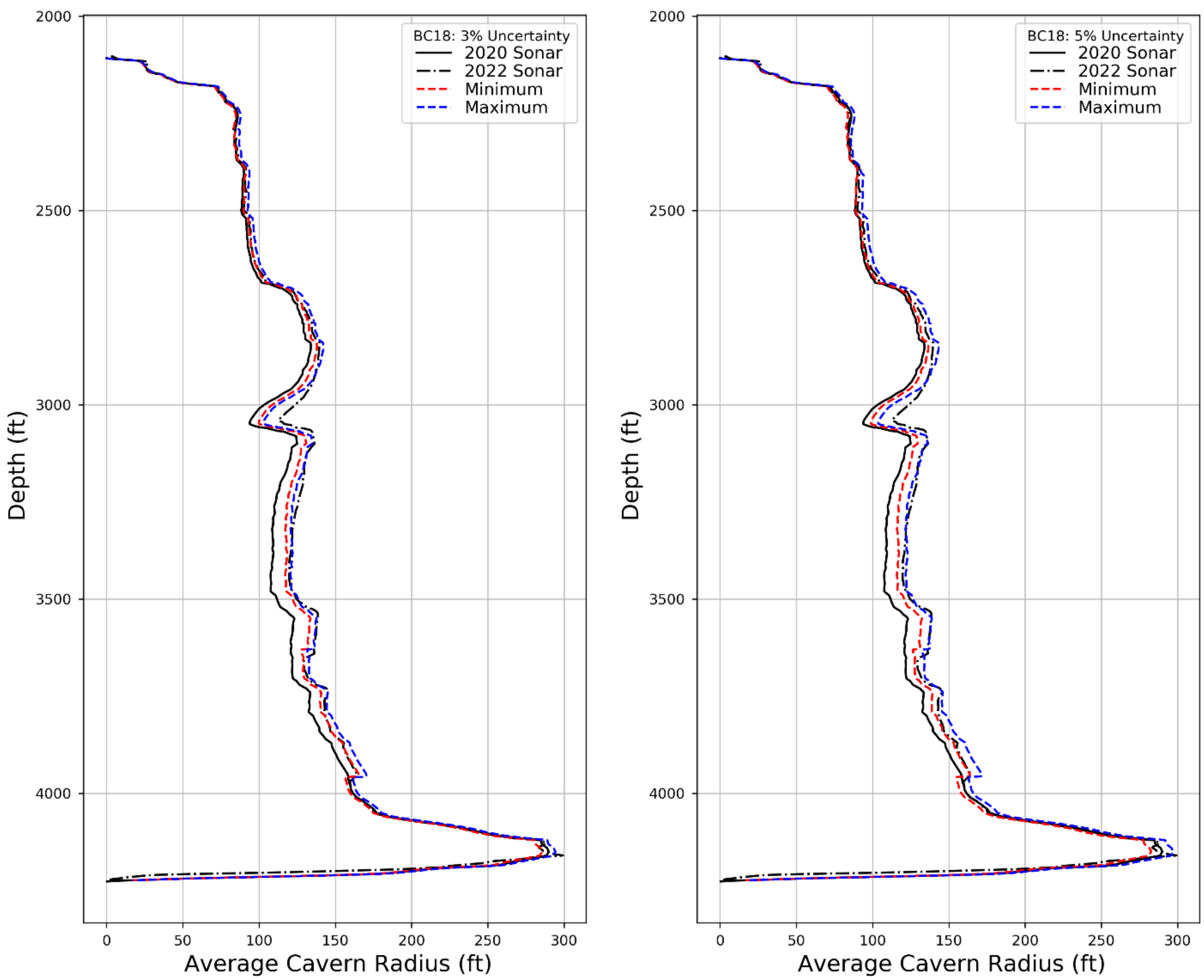

Figure 12. Results of SANSMIC modeling for BC-18. Results for combined uncertainties when the injection volume and sonar surveys are each subject to ±3% (left) and ±5% (right) uncertainty.

The BH-109 cavern had a sonar in 2020 which provided the baseline cavern geometry. The injection history for BH-109 consisted of injections in 2020-2022 totaling about 7 MMB (1.1 MM m^3). For the purposes of SANSMIC modeling, these injections were divided into four phases, each with a different injection rate applied to result in the same total injection volume over all four phases (Figure 13). This is consistent with the methodology used in our typical leaching analyses [5].

An identical simulation methodology was applied to BH-109 as was applied to BC-18 and the hypothetical, cylindrical caverns above. Injection rates were scaled up or down for various levels of uncertainty and the sonar survey geometries were also adjusted by the same levels of uncertainty. Combinations of the two uncertainty types were applied to additional simulations as above. The resultant geometries (minimum and maximum radii at each depth) are shown in Figure 14 for ±3 and ±5 levels of uncertainty. The original and final sonars are also shown for comparison.

In the growth region (depths of ~2300-4300 ft, 700-1300 m), SANSMIC-predicted growth generally agrees with the resultant growth shown by the 2022 sonar. In the lower part of the cavern, SANSMIC-predicted results exceed the sonar results even for the ±5 level of uncertainty. This can be attributed to another limitation of the SANSMIC code: it does not account for the floor rise/creep observed between the 2020 and 2022 sonars. Because the SANSMIC model is limited to leaching, the change in floor level is not accounted for and thus SANSMIC slightly over-predicts leaching near the cavern floor. As a result, SANSMIC also under-predicts leaching further up in the cavern where the 2022 sonar shows additional cavern growth. SANSMIC is able to capture the appearance of a “ledge” rather than smooth radial growth at a depth of about 3200 ft (980 m). The abrupt change in growth is due to the change in the depth of EOT during oil movements between Phases 3 and 4. By raising the EOT from about 4150 ft to about 3100 ft. In that region of new growth, there is a small overprediction by SANSMIC that falls within the ±3-5% bounds.

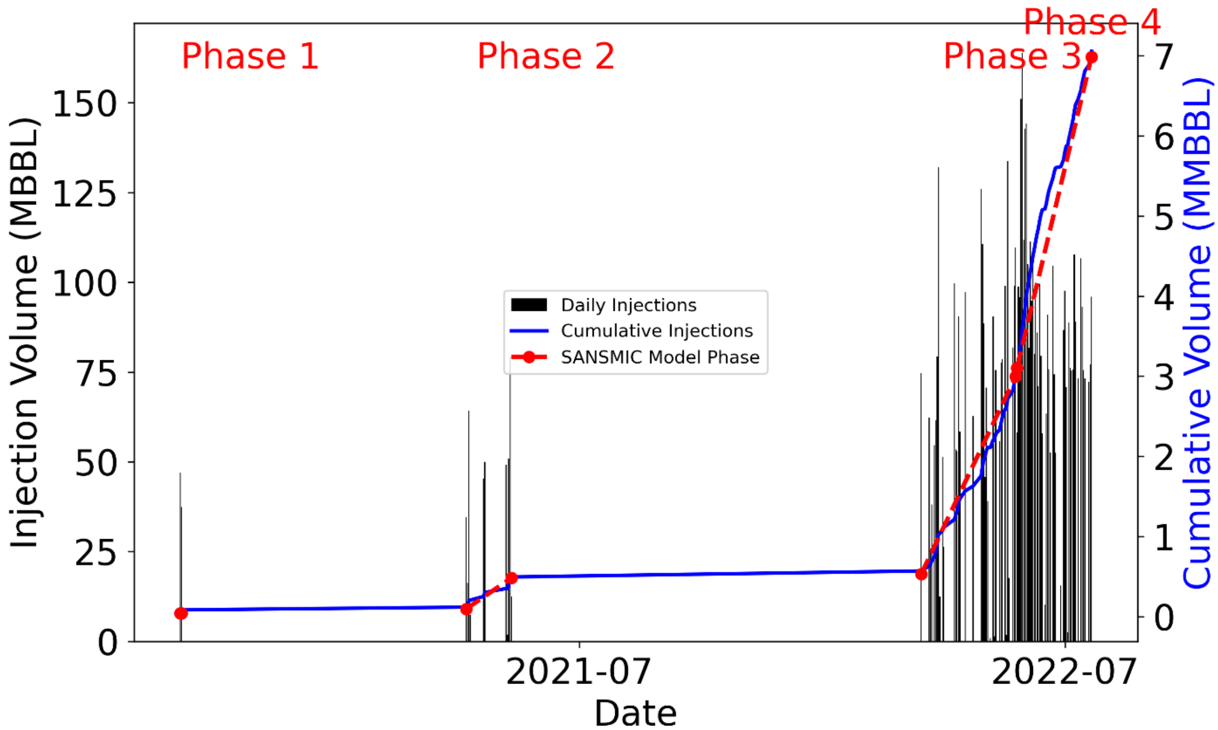

Figure 13. Raw water injection history for BH-109 between 2020 and 2022 sonars.

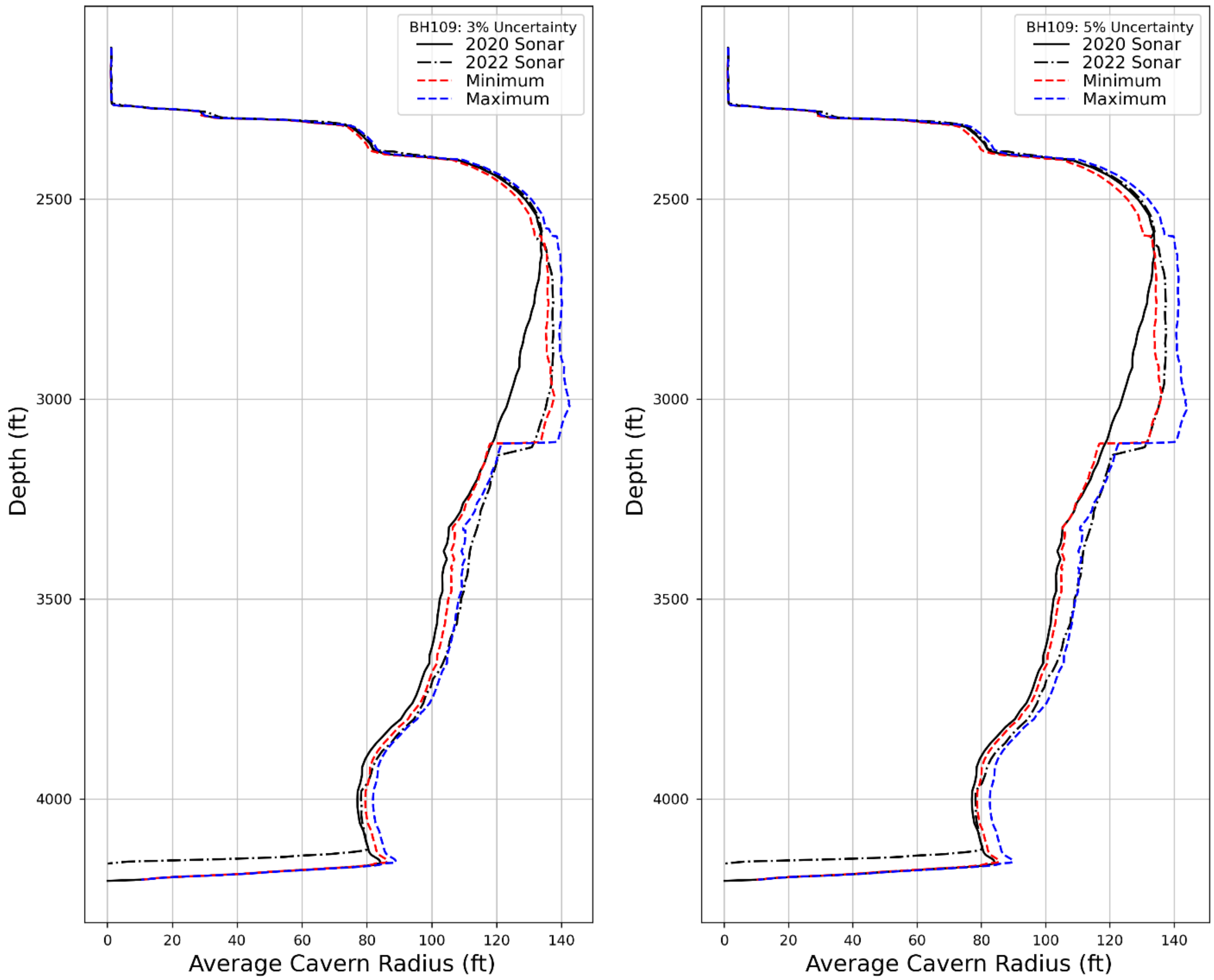

Figure 14. Results of SANSMIC modeling for BH-109. Results for combined uncertainties when the injection volume and sonar surveys are each subject to ±3% (left) and ±5% (right) uncertainty.

Conclusions

We find that current levels of uncertainties in raw water injection volumes and sonar surveys to be relatively unimpactful to the results of our leaching models. At the same uncertainty level, injection volumes are much less impactful than sonar surveys. For a “typical” uncertainty of ±3% in the injection volume and ±1% uncertainty in the sonar survey, we expect about ±1.5 ft (±0.5 m) uncertainty in the location of the cavern wall. We still expect good agreement with follow-on sonars (where available); however, we also note the limitations of the current SANSMIC code, as it does not account for vertical leaching, salt falls and creep/floor rise. As we move forward with planned changes to SANSMIC, we believe we have a good software basis.

Acknowledgements

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