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Automation of Plot Generation for Strategic Petroleum Reserve Cavern Leaching Monitoring

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ABSTRACT

Monitoring cavern leaching after each calendar year of oil sales is necessary to support cavern stability efforts and long-term availability for oil drawdowns in the U.S. Strategic Petroleum Reserve. Modeling results from the SANSMIC code and recent sonars are compared to show projected changes in the cavern's geometry due to leaching from raw-water injections. This report aims to give background on the importance of monitoring cavern leaching and provide a detailed explanation of the process used to create the leaching plots used to monitor cavern leaching. In the past, generating leaching plots for each cavern in a given leaching year was done manually, and every cavern had to be processed individually. A Python script, compatible with Earth Volumetric Studio, was created to automate most of the process. The script makes a total of 26 plots per cavern to show leaching history, axisymmetric representation of leaching, and SANSMIC modeling of future leaching. The current run time for the script is one hour, replacing 40-50 hours of the monitoring cavern leaching process.

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EXECUTIVE SUMMARY

The United States Strategic Petroleum Reserve stores crude oil in preexisting caverns along the Gulf Coast. Raw water drawdowns push oil out of the cavern to execute congressionally mandated oil sales. Raw water leaches the sides of the cavern at a faster rate when compared to fully saturated brine; thus, each leached cavern must be monitored for available drawdowns and cavern stability (Eldredge et al., 2013). Sandia National Laboratories uses Earth Volumetric Studio (EVS) software to visualize leaching impacts. Raw water leaching is monitored through past and recent sonars. Leaching is also modeled using the SANSMIC code for comparison with sonar data.

Annual leaching reports have provided comparisons of sonar data and modeling results with cavern geometry being the typical means of comparison. There are three central figures produced, with a total of 26 plots generated for each cavern. The first figure represents the leaching history. The leaching history is shown through a comparison of two sonars- one being the most recent and the second being an earlier sonar.

The second figure focuses on the axisymmetric representation of the most recent sonar. This figure compares the current sonar and its axisymmetric representation to illustrate the ovality of the cavern. The ovality of a cavern can aid in predicting leaching patterns, and the axisymmetric representation from sonar data is the input for the leaching prediction model. Hence, a comparison with the sonar is essential to the monitoring of cavern geometry development.

The third and final figure used to monitor leaching effects incorporates the Sandia Solution Mining Code (SANSMIC) cavern geometry prediction based on sonar data and raw water injection histories. Leaching predictions are routinely simulated because sonars are not always available after a leaching period and are resource-intensive. For a given cavern, new sonars are performed approximately every 5-10 years, while oil sales may occur in any year. Thus, leaching modeling provides a means to monitor cavern geometry development between sonars.

Leaching is monitored at the end of every calendar year, and an average of 30 caverns are reviewed. With more than 24 plots for each cavern, a total of more than 700 plots can be generated for each leaching calendar year. In the past, each plot has been created individually for every cavern in that leaching period. Although some of the processes to produce these plots require technical decision-making and cannot be fully automated, most of the settings to manipulate the visual field can be automated. EVS has comprehensive Python scripting of most functions in the application, so what could be automated was done in the current work through use of the scripting function in EVS.

Python scripting within EVS software was used to develop a script that can process each cavern as specified by the user, typically those that experienced leaching in a given calendar year. The script loads the most recent sonar, a previous sonar, axisymmetric cavern geometry from the most recent sonar, and the cavern geometry SANSMIC representation for each cavern into EVS. All presets and parameters for each leaching plot type have been coded into the script. Each file is uploaded into its respective module in EVS when the script runs and outputs 26 different plots for each cavern. The script is currently over 3000 lines long and was split into five sections. These sections are EVS/Python libraries, dictionaries to store slice depth data, sonar file paths, functions, and nested loops in which the leaching plots are created. Before running the script for a new leaching year, the slice depth dictionaries must be updated. Although there is still a manual component to plotting leaching within the caverns, creating the EVS-compatible Python script has automated most of the process, saving about 40-50 hours of work for each leaching calendar year

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
BC	Bayou Choctaw site
BH	Big Hill site
BHF	Braden head flange
BM	Bryan Mound site
DOE	Department of Energy
EOT	depth of end of brine string tubing
EVS	Earth Volumetric Studio Software
MMB	million barrels
OBI	oil-brine interface
SANSMIC	**San**dia **S**olution **Mi**ning **C**ode software
SNL	Sandia National Laboratories
SPR	Strategic Petroleum Reserve
WH	West Hackberry site

1. INTRODUCTION

1.1. Cavern Leaching at the SPR

The United States Strategic Petroleum Reserve (SPR) is a crude oil storage system run by the U.S. Department of Energy (DOE). The reserve consists of underground oil storage caverns in salt domes near the Gulf of Mexico. There are 60 active caverns spread across four sites in Texas and Louisiana. The Big Hill (BH) and Bryan Mound (BM) sites are in Texas and Bayou Choctaw (BC) and West Hackberry (WH) are in Louisiana. The purpose of the SPR is to protect the U.S. from crude oil supply interruption through storage, acquisition, and distribution. When oil is needed to fulfill emergency sales or exchanges, raw water is injected to withdraw stored oil. When the raw water (which is not salt-saturated) is injected into the caverns, the water leaches the cavern walls. Oil withdrawals, or drawdowns, may affect the cavern's stability and the number of available future drawdowns, so it is vital to monitor these effects often (Eldredge et al., 2013).

Drawdown leaching occurs when the raw water is injected at the end of the brine string tubing (EOT), which pushes oil to the top and out of the cavern (Figure 1-1). During drawdowns, leaching takes place between the EOT and oil-brine interface (OBI) positions in the cavern. Sales involve partial drawdowns where part of the oil is withdrawn from a cavern at one time. For partial drawdowns, leaching happens to a greater extent near the EOT, where the greatest contact time between the water and salt walls occurs. The raw water reduces the salinity in the surrounding brine until it reaches the final OBI, where the contact time is less, so a "flare" pattern is often observed with partial drawdowns associated with sales (Figure 1-2). To better visualize raw water's leaching effects on each cavern, plots comparing the most recent and previous sonar surveys are assembled into figures to show cavern volume and shape change.

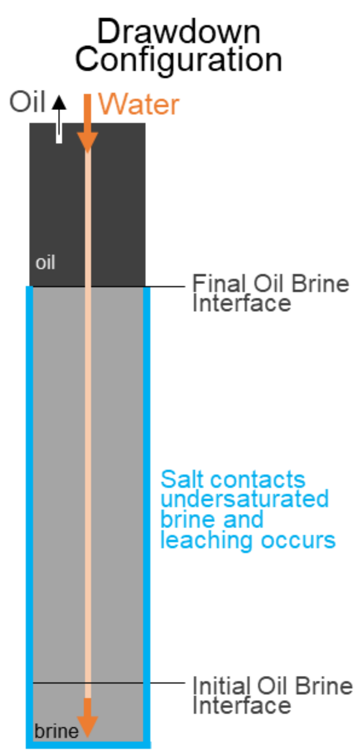

Figure 1-1. Schematic of drawdown configuration which results in cavern wall leaching (Zeitler et al., 2021).

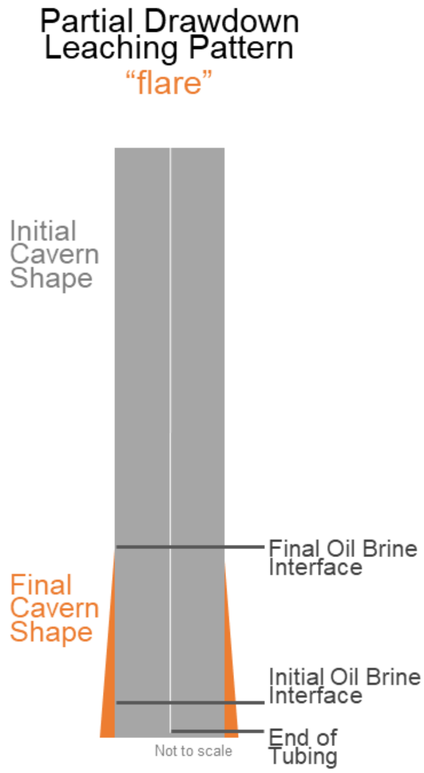

Figure 1-2. Schematic of leaching pattern from a partial drawdown (Zeitler et al., 2021).

1.2. Creation of Leaching Plots Using Sonars

For the past several years, Sandia National Laboratories (SNL) has used Earth Volumetric Studio (EVS) software to visualize leaching impacts due to raw water injections through past and recent sonars. Sonar surveys are used to calculate the volume of the cavern and monitor cavern shape. The sonar reports often provide some cross-sections in the cavern, but the EVS software outputs a 3-D visualization of the whole sonar, so cross-sections can be taken from anywhere in the cavern. EVS EVS has also been used to visualize predictions of leaching outcomes created by the **San**dia **S**olution **Mi**ning **C**ode (SANSMIC) software model. The geographic data from the sonar and SANSMIC files are analyzed and, through visualization tools, produce plots of sonars and various cross-sections. The plots are then combined into figures that can show the leaching history and leaching prediction for each cavern. In the past, each plot has been created manually for every cavern in that leaching period. Although some of the processes to produce these plots require technical decision-making and cannot be fully automated, most of the settings to manipulate the visual field can be automated. EVS has comprehensive Python scripting of most functions in the application, so what could be automated was done through the scripting function in EVS.

1.3. Report Organization

The organization of this report is given as follows. First, the methods that monitor leaching are given in three sub-sections covering the main categories for the leaching figures. There are three main figures produced with the plots from this process to convey leaching monitoring and prediction. Section 2.1 provides an overview for the leaching history figure and its significance to understanding leaching patterns. Section 2.2 shows the relevance of axisymmetric representations of previous sonars and how they are useful for assessing the cavern’s ovality or geometric symmetry.

The last section that focuses primarily on the plots and figures themselves is Section 2.3, which includes the use of plots of SANSMIC modeling output to predict leaching behavior and comparison to previous sonars and axisymmetric representations.

The rest of the report focuses on the automation process for the plots used for the leaching figures mentioned above. Section 3 is a brief overview of the EVS settings needed for setting up an application compatible with the current Python script. The report concludes with Section 4, which discusses the current and future capabilities of the Python scripting that automates the leaching plots.

2. DESCRIPTION OF LEACHING MONITORING FIGURE TYPES

2.1. Leaching History

Leaching effects are inspected annually in the SPR Caverns, and SNL produces a Cavern Leaching Monitoring report to document the impacts of sales operations on the long-term integrity of the caverns. Caverns are selected for leaching evaluation and SANSMIC modeling based on the criteria of a minimum injected volume of raw water. In CY20, this minimum volume was 10,000 bbls of raw water (Zeitler et al., 2021). Typically, for each cavern considered in a leaching report, a set series of figures is presented. In some cases, additional figures are used, but this section discusses the typical figure types, what they represent, and how they are useful for monitoring leaching. There are three principal figure types, consisting of 6-7 subplots each. Figure type 1 (leaching history), Figure type 2 (axisymmetric representation), and Figure type 3 (SANSMIC model) are discussed in sections 2.1, 2.2, and 2.3, respectively.

The first figure used in leaching monitoring is the leaching history for that cavern. The leaching history is shown through two sonars, the most recent and an earlier sonar. With caverns that have more static conditions and fewer oil sales, older sonars are sufficient to show the volume change; however, in caverns with more dynamic conditions, the sonar before the most recent sonar is preferable. It is important to note that the differences between the cavern's geometry are not all directly caused by leaching. Some geometry changes can also be attributed to salt falls, floor rise, or natural creep rates. The relative impact of each of these processes on cavern geometry is dependent on time, cavern pressure histories, homogeneity of salt, raw water injection histories, and possibly other factors. Figure 2-1 shows the leaching history for BH-101. Each leaching history figure shows the sonar profiles of the most recent sonar and a previous sonar and their vertical and lateral cross-sections at pre-determined depths where cavern volume has changed, and unique features are prominent.

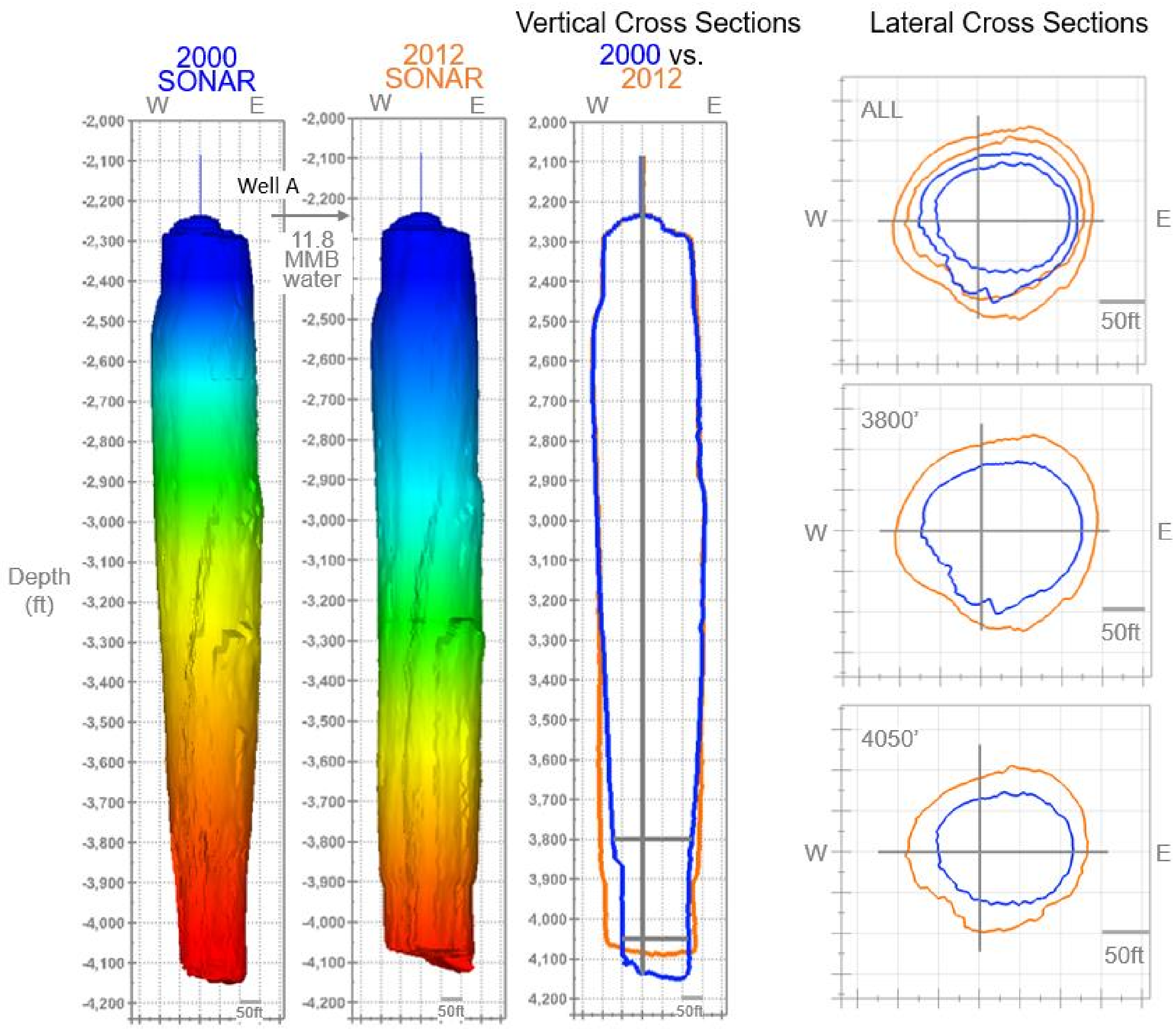

Figure 2-1. Example leaching history for BH-101 (all plots are from leaching script)

There is a total of six plots in Figure 2-1, but a total of nine are produced for each cavern's leaching history. The three additional plots come from the different viewing angles of the two sonars. It is important to assess the sonar from north and west angles because important geometric characteristics can often be seen from only one side of the sonar. The viewing angle that showcases the most irregularities in the cavern shape or the largest volume change between sonars is selected for the figure. Table 2-1 gives a summary of each plot type and the level of automation.

Table 2-1. Leaching history list of plots

Leaching history plot type	Number of plots	Automated?
Vertical profiles of the most recent and previous sonars (north and west)	4	Yes
Vertical cross-section comparing the most recent and previous sonars (north and west)	2	Partially- need depth(s) of interest for horizontal reference lines

Leaching history plot type	Number of plots	Automated?
Lateral cross-sections at depth(s) of interest	3	Partially- need depth(s) of interest for each cross-section

2.1.1. Vertical Profiles and Cross-Section

The vertical profiles of the most recent and a previous sonar are used to show how leaching impacted the whole cavern. Between sonars, the greatest change is typically observed happens near the EOT, as discussed in the introduction section. As a general trend, caverns tend to widen and have floor rise. The floor rise is usually attributed to natural creep rates and salt falling to the bottom from the cavern's walls. The widening of the base is due to the water injections leaching the salt walls between the EOT and OBI, which are typically towards the bottom of the cavern. It is essential to view the vertical profiles of the sonars to see if any new features have formed, such as flares and shelves. As mentioned in the introduction, flares are created when fresh water is injected at the EOT, typically near the cavern floor. Shelf features may be created in the cavern geometry when the EOT is not at the cavern's bottom, as the most significant leaching occurs far from the cavern floor and creates a shelf.

On the left in Figure 2-1, sonar geometries for the BH-101 cavern from 2000 and 2012 are plotted with the surface color-coded by depth, with red being the deepest. A comparison plot of vertical cross-sections through each sonar is shown in the middle of the figure, with the 2000 sonar represented by the blue line and the 2012 sonar represented by the orange line. The vertical cross-section placements are from the same well coordinates from where the sonar was taken from. The vertical, grey lines down the center of the cavern represent the well location where the sonar was surveyed. For BH-101, the sonar was taken down the A well, and the grey line represents the x and y coordinates of the A wellhead. Lastly, the grey horizontal lines in the vertical cross-section represent the depths from which the lateral cross-sections were taken.

2.1.2. Lateral Cross-Sections

The leaching pattern at a given depth is shown through the lateral cross-sections, as shown in the righthand portion of Figure 2-1. For caverns that follow a more cylindrical, geometrically symmetrical shape, leaching typically follows an even radial pattern. However, caverns that have distinctive features or are known to have a higher concentration of insolubles in an area may show non-uniform leaching. There are three cross-sections in the leaching history figure, two of them are at pre-determined depths of interest, and the third plot compares the two cross-sections. Before the lateral cross-section plots are created, the two sonars are inspected to locate depths where leaching features are emphasized, or the largest change in volume is shown in the horizontal plane. These depths are typically chosen deeper in the cavern because more raw water leaching occurs near the EOT, which is typically near the cavern floor. Comparisons between the two depths are important because it emphasizes how the cavern shape changes vary with depth. The grey vertical and horizontal lines represent the location of the well, as in the vertical cross-section. The vertical line represents the location of the northing slice, and the horizontal line represents the location of the easting slice. Lastly, the cross-sections help visualize the quantitative amount of leaching. The axes show that about 20 feet of radial leaching occurred in cavern BH-101.

2.2. Axisymmetric Representation

The second figure used in leaching monitoring is the axisymmetric cavern geometry representation comparison to the recent sonar. The axisymmetric representation is created by averaging the cavern radius at each depth of the sonar. The axisymmetric representation accurately represents the volume at each depth slice but does not accurately represent the geometric asymmetry (Chojnicki, 2020). A comparison between the recent sonar and the axisymmetric representation can help determine the ovality of the cavern with depth. Caverns with circular cross-sections generally follow a radial leaching pattern; however, caverns with more ovality can follow an asymmetrical pattern. Figure 2-2 shows the comparison between the 2012 sonar and its axisymmetric representation for BH-101. Each axisymmetric representation figure shows the profiles of the recent sonar and its axisymmetric representation and their vertical and lateral cross-sections at pre-determined depths. The axisymmetric representation is important because the current version of the SANSMIC software relies on 1-D axisymmetric cavern geometries as input and similarly produces only 1-D cavern geometries. The comparison provided in this type of figure indicates to what extent the actual initial cavern geometry (from the sonar) differs from the initial SANSMIC model geometry, which is important in interpreting observed changes in cavern geometry.

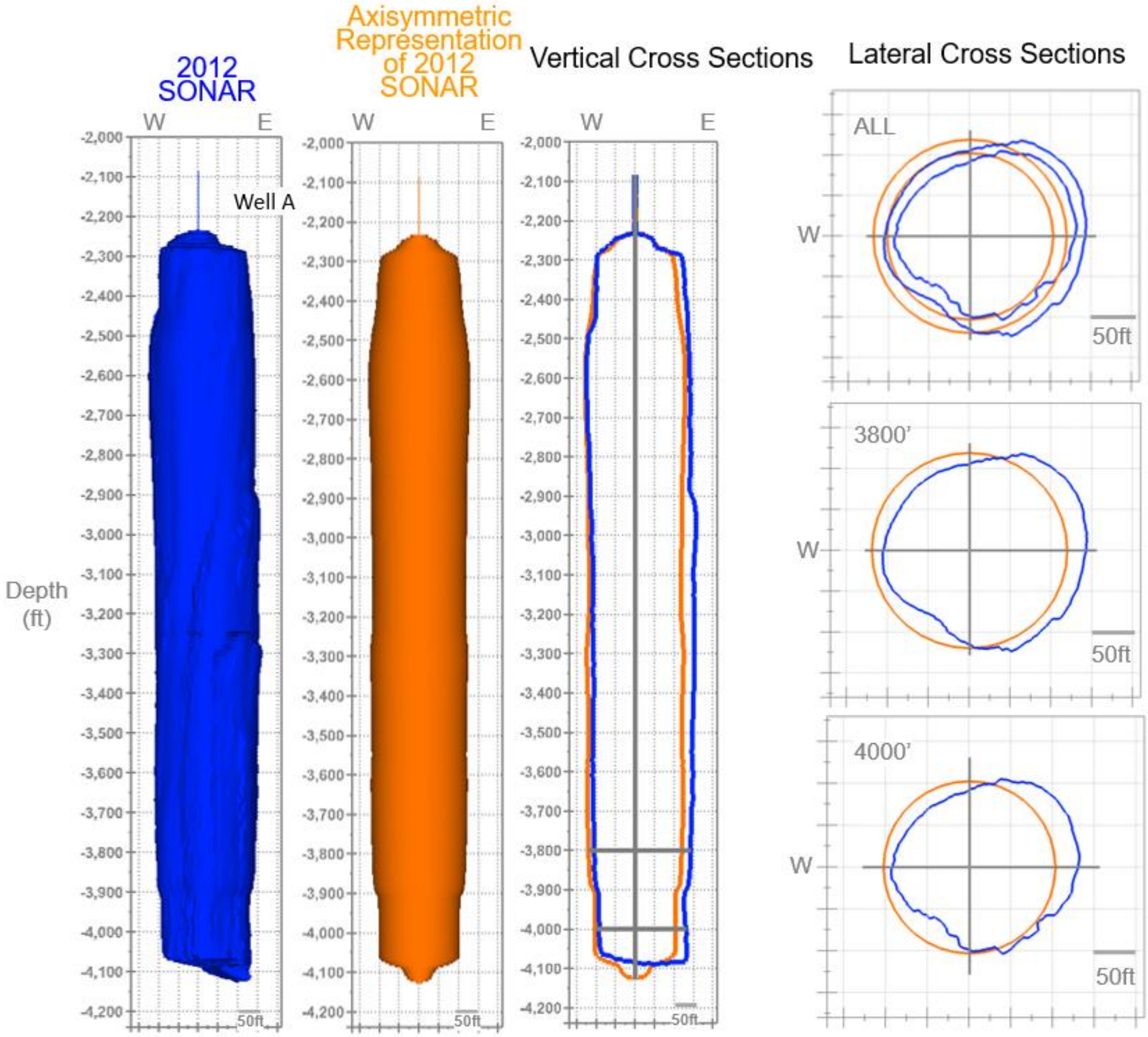

Figure 2-2. Example of 2D axisymmetric representation (orange) of 3D cavern geometry (blue) for BH-101 (all plots are from leaching script)

There is a total of six plots in Figure 2-2, but a total of nine are produced for each cavern's axisymmetric representation comparison The three additional plots come from the different viewing angles of the recent sonar and axisymmetric representation, like the leaching history figure. The viewing angle that showcases the most ovality in the cavern is selected for the figure. Table 2-2 gives a summary of each plot type and the level of automation.

Table 2-2. Axisymmetric representation comparison list of plots

Axisymmetric representation plot type	Number of plots	Automated?
Vertical profile of recent sonar- solid blue (north and west)	2	Yes
Vertical profile of axisymmetric representation- solid orange (north and west)	2	Yes

Axisymmetric representation plot type	Number of plots	Automated?
Vertical cross-section comparing recent sonars and axisymmetric (north & west)	2	Partially- need depth(s) of interest for horizontal reference lines
Lateral cross-sections at depth(s) of interest	3	Partially- need depth(s) of interest for each cross-section

2.2.1. Vertical Cross-Sections

The vertical profiles of the recent sonar and its axisymmetric representation show how cylindrical the cavern is and where the location of the center of mass. On the left in Figure 2-2, the recent sonar is shown in blue, and the axisymmetric representation is shown in orange. The blue sonar shows that BH-101 is primarily cylindrical, with some irregularities near the top and towards the cavern's bottom. Most of the caverns from Big Hill follow closely to this cylindrical shape as they are the most recent DOE cavern wells. Considerable differences between sonars and their axisymmetric representation are mostly seen at BC, BM, and WH.

A comparison of vertical cross-sections from the recent sonar and its axisymmetric representation is shown in the middle, with the current sonar represented by the blue line and the axisymmetric representation represented by the orange line. Like the leaching history plots, the vertical cross-sections are from the same well coordinates from where the sonar was taken and the grey vertical line represents the well's coordinates for that sonar. The two grey horizontal lines represent the locations where the lateral cross-sections were taken from. The vertical cross-section comparison plot emphasizes the cavern's center of mass slightly northeast in position to the A well.

2.2.2. Lateral Cross-Sections

The ovality at a given depth is shown through the lateral cross-sections, as shown in the righthand portion of Figure 2-2. The lateral cross-sections can also show interesting features in the salt at a specific region or covering a certain length. The grey vertical and horizontal lines represent the exact location of the well, as in the vertical cross-section. The vertical line represents the northing slice, and the horizontal line represents the easting slice. There are three cross-sections in the axisymmetric representation, two of them are at pre-determined depths of interest, and the third plot compares the two cross-sections. The pre-determined depths are at the locations of most interest, usually at the bottom of the cavern or locations of extreme ovality. The comparison between the two lateral cross-sections reveals whether the ovality is continuous throughout the cavern or varies with depth. BH-101 experiences ovality with a center of mass towards the east and higher up in the cavern and a “knob-like” feature towards the west.

2.3. SANSMIC Model

The third and final type of figure used to monitor leaching effects compares the cavern geometry generated from SANSMIC modeling against the original cavern geometry. While the second and third figures look similar, they serve two different purposes. The Axisymmetric Representation Figure highlights cross-sections to show cavern ovality and unique geometry features. In contrast, the SANSMIC Model Figure shows how much leaching is predicted at the EOT and OBIs after that CY of oil sales. Since the axisymmetric representation of the sonar is the input for the SANSMIC model, the second figure is also helpful to interpret how the SANSMIC prediction will match up to future sonars with the same amount of raw water injected.

Sonars are the best way to monitor leaching; however, they are resource-intensive and don't always coincide after leaching periods for most caverns. Thus, leaching predictions are essential to anticipate cavern geometry changes when no current sonar is available. To accomplish this, SNL developed the SANSMIC computer code in 1981 (Russo, 1981). SANSMIC was later modified several times to improve the shaping of the predicted cavern to the actual leached caverns.

The SANSMIC code is used to predict the development of axisymmetric caverns by calculating volume changes. This code contains four leach modes- withdraw, direct, reverse, and leach-fill (Weber, 2016). For annual leaching monitoring reports, withdrawal leaches are assumed. SANSMIC uses parameters such as brine string height (relative to the cavern floor), injection rates of raw water, and stage duration (Weber, 2016). The model computes the effects these parameters have below the OBI, and a 1-D, axisymmetric representation, with an equivalent leached-cavern volume is the SANSMIC output.

Figure 2-3 compares the 2012 sonar, its axisymmetric representation, and the "2020 SANSMIC prediction". The 2012 sonar is shown in blue, the axisymmetric representation of the sonar, which is the SANSMIC input, is shown in orange, and the SANSMIC output is shown in magenta. There are seven plots in Figure 2-3, but a total of eleven plots are produced for each cavern's SANSMIC prediction. The four additional plots come from the different viewing angles of the four vertical plots. As mentioned in previous sections, the plot with the best view of volume change or unique leaching features is chosen. There is a supplementary plot not seen in Figure 2-3 but explained in Section 2.3.3. Table 2-3 gives a summary of each plot type and the level of automation (recent sonar and axisymmetric representation are not included in this table, but can be found in Table 2-2).

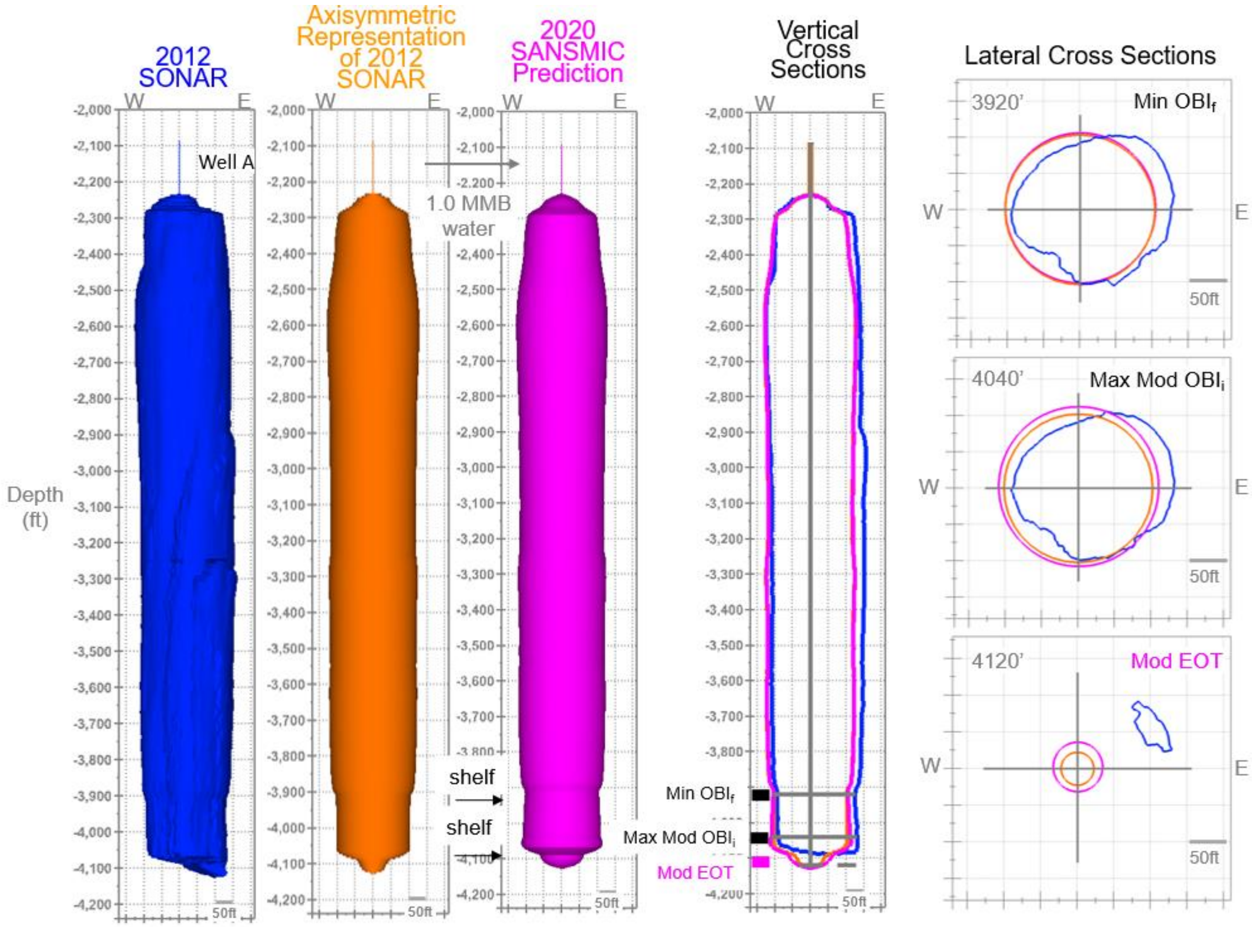

Figure 2-3. Example of 2020 SANSMIC results for BH-101 (all plots are from leaching script)

Table 2-3. SANSMIC prediction list of plots

SANSMIC prediction plot type	Number of plots	Automated?
Vertical profile of SANSMIC prediction-solid pink (north and west)	2	Yes
Vertical cross-section comparing recent sonar, axisymmetric, and SANSMIC prediction (north & west)	2	Partially- need OBI-f, OBI-I, and EOT for horizontal reference lines
Lateral cross-sections at depth(s) of interest	3	Partially- need OBI-f, OBI-I, and EOT depths for each cross-section
*Zoomed in vertical cross-section comparing recent sonar, axisymmetric, and SANSMIC prediction in leaching region	1	Partially- need OBI-f, OBI-I, and EOT for horizontal reference lines
*Plot not shown in Figure 2-3, but explained in section 2.3.3		

2.3.1. Vertical Cross-Sections

The profiles in Figure 2-3 of the most recent sonar and its axisymmetric representation are the same as those in Figure 2-2. The SANSMIC output and the vertical cross-section comparison between all three plots are the furthest right of the vertical plots. The SANSMIC modeling does not include the Braden head flange (BHF) location , so to properly align the SANSMIC prediction with the other two plots, the SANSMIC depths must be translated vertically by the height of the BHF. Between the SANSMIC input and output subplots, a grey arrow represents the amount of raw water injected to produce the SANSMIC prediction. For Figure 2-3, there was a total of 1.0 MMB of freshwater injected into BH-101 from when the 2012 sonar was taken to the end of the calendar year 2020.

Like the two previous figures, the grey vertical line in the comparison plot represents the well's coordinates for that sonar. The three grey horizontal lines represent the locations where the lateral cross-sections were taken. For the SANSMIC prediction figure, the three cross-sections stay consistent between each cavern- the final OBI, initial OBI, and the EOT. The final OBI is also known as the minimum OBI because the OBI's depth rises after water is injected into the cavern and is the shallowest depth in all leaching phases (Zeitler et al., 2021). The initial OBI that is plotted is the deepest initial OBI depth over all leaching phases (in leaching reports, a "modified" OBI is given as the OBI height output by the SANSMIC code after rounding to the nearest simulation cell edge) (Zeitler et al., 2021). There is only one EOT depth for a typical leaching period; however, brine string cuts and salt falls that destroy the string can occur and produce two EOT depths for that leaching period. Two EOT depths are very uncommon, so only one EOT is plotted.

In Figure 2-3, predicted leaching effects are not as noticeable in the vertical cross-section because only 1.0 MMB of fresh water was injected. However, the vertical cross-section shows where the OBIs and EOT are relative to the full cavern, which may be important for interpreting cavern geometry changes. For a minimum OBI higher up in the cavern, leaching is distributed over a more extended region, which decreases the amount of leaching in a particular lateral cross-section. For a minimum OBI located deeper in the cavern (closer to the EOT) leaching is concentrated over a shorter vertical region, which increases leaching for a particular lateral cross-section. Lastly, the position of the EOT will indicate whether a shelf or flare is likely to happen. As discussed in the leaching history section, shelves may develop when the EOT is distant from the cavern floor, and flares may develop when the EOT is near or at the cavern floor when there is repeated leaching over the same vertical interval. The two shelves seen in BH-101's SANSMIC prediction can be from previous leaching events and existing cavern geometry. The shelf near the minimum OBI can be observed in the 2012 sonar, but there is not another sonar available to confirm if the shelf increased or is still there. The leaching towards the bottom of BH-101 is not pronounced enough to be considered a leaching-induced "flare".

2.3.2. *Lateral Cross-Sections*

The predicted amount of leaching at a given depth is shown through the lateral cross-sections, as shown in the righthand portion of Figure 2-3. The most leaching is at the EOT and tappers off until it reaches the minimum OBI. The grey vertical and horizontal lines represent the exact location of the well, as in the vertical cross-section. The vertical line represents the northing slice, and the horizontal line represents the easting slice. While the sonar is included in the lateral cross-sections, the axisymmetric representation (SANSMIC input) and SANSMIC output are compared for predicted leaching effects. However, the current cavern's geometry is important to keep in the context of the plot, since some geometry information is lost when converting from 2-D sonar data to a 1-D axisymmetric representation. Lastly, the cross-sections help visualize the quantitative amount of predicted leaching. The axes indicate ~10 feet of predicted leaching at the EOT and ~ 5 feet at the maximum modified OBI for BH-101.

2.3.3. *Predicted Leaching Region*

A plot often used in the SANSMIC prediction figures that is not included in Figure 2-3 is the predicted leaching region plot, as shown in Figure 2-4. In caverns with low injected water volumes (<1.0 MMB), the vertical cross-section comparison and lateral cross-sections can be hard to visualize leaching effects. So, an additional plot is created that is zoomed in where the predicted leaching occurs. The predicted leaching region outlined in Figure 2-4 will always be between the minimum OBI and EOT when looking at a SANSMIC output. Since this plot contains no axes, only qualitative observations can be made.

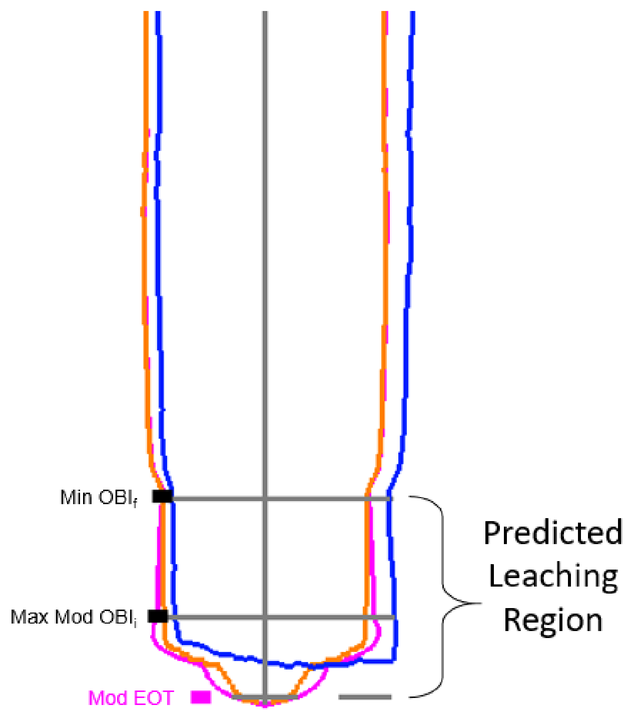

Figure 2-4. 2020 SANSMIC predicted leaching region for BH-101 (plot from leaching script)

2.3.4. *Cumulative Oil Volume*

The last figure that is mentioned in this section is the Cumulative Oil Volume Figure, show in Figure 2-5. This figure has not been included in past leaching reports, but has been used in past leaching monitoring presentations and is useful when paired with the Leaching History Figure (Figure 2-1). The cumulative oil volume is shown on the y-axis and time is shown on the x-axis. This plot is used in conjunction with the leaching history figure because it shows the oil volume and water injected between sonars and since the latest sonar. Like the leaching history, the previous sonar is blue, and the recent sonar is orange. The blue line indicates when the previous sonar was taken, and the orange line indicates when the recent sonar was taken. The first grey arrow between each sonar shows how much freshwater was injected, and the second grey arrow shows how much water was injected since the recent sonar. The water volume is important for the leaching history to see how the cavern behaves with a certain amount of raw water injected.

In the case of BH-101, 11.8 MMB of water was injected between the 2000 and 2012 sonars. The observed cavern volume changes between the 2000 and 2012 sonars in Figure 2-1 can help predict future leaching effects by the 1.0 MMB water injected after the 2012 sonar in BH-101. The 1.0

MMB is the amount of water injected after the 2012 sonar to the end of 2020, and this amount was used for the 2020 SANSMIC modeling prediction. Even though this graph was not automated through the Python scripting function in EVS, this graph can be partially automated through Excel Macro, making it an automated leaching figure, and very useful when looking at leaching history and predicting future leaching.

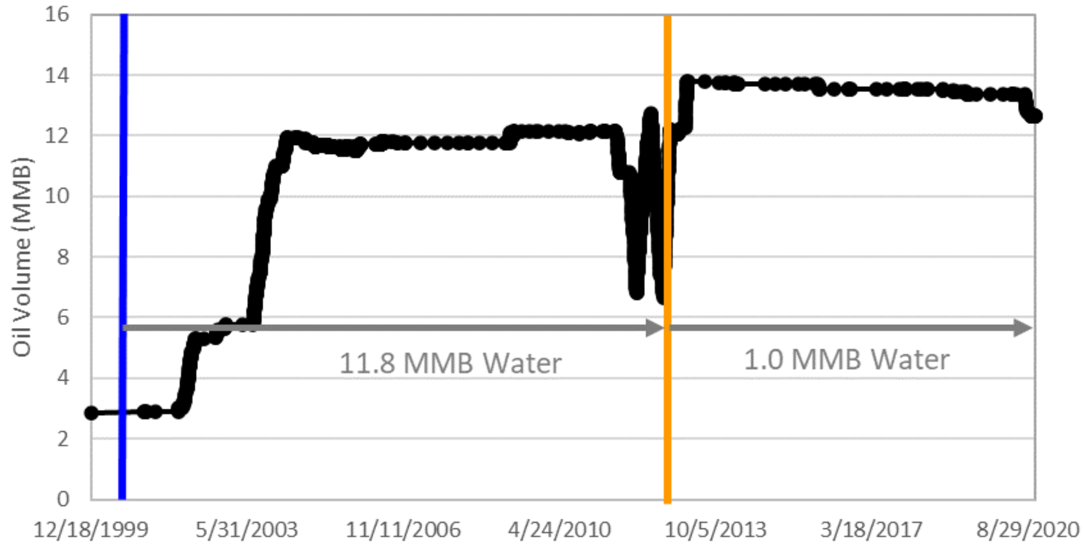

Figure 2-5. Cumulative oil volume for BH-101

3. EARTH VOLUMETRIC STUDIO SOFTWARE

3.1. User Interface

Earth Volumetric Studio is a standalone Windows program that analyzes analytical and geophysical data (C Tech, 2021). EVS is a modular software that performs the analysis and visualization for the leaching monitoring task in the SPR. There are two interfaces built into the program. The advanced or "edit" mode uses multiple modules and parameters to analyze and visualize earth science data, and the presentation mode uses pre-built applications for centered visual displays. The edit mode will be covered in this report; however, the presentation mode is useful when displaying modeling results in the viewer. The EVS application contains separate windows for the different functions offered in the software in a standard layout, shown in Figure 3-1.

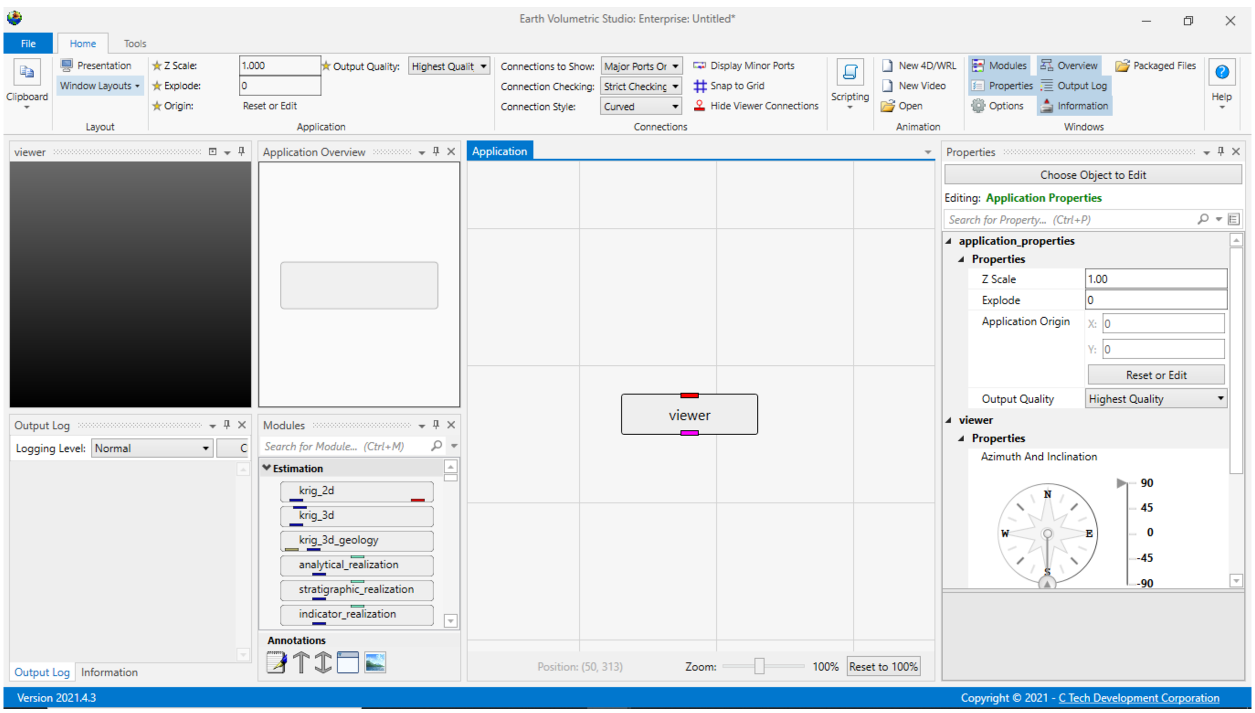

Figure 3-1. EVS advanced window layout

There are six primary sub-windows used when running EVS for leaching monitoring purposes.

1. The viewer is in the upper left. The default color is a black gradient and is empty until you have an application that has run. The output images come from the viewer.
2. Below the viewer is the Output Log which provides useful information when modules run, such as loading files, output images, and status updates when scripting, such as warning or error messages.
3. To the right of the Output Log window are the Modules which are listed in 19 sub-libraries. When searching for a module, type the first couple of letters of the specific module. A list will expand to show only those modules that include those letters. You can then copy any module to your Application by selecting it and hitting ENTER, double-clicking, or dragging it to the Application.

4. Above the Modules is the Application Overview window. It automatically resizes to show you a thumbnail view of your Application. It allows you to navigate, zoom and pan your Application.
5. To the right of the Application Overview is the Application window in the center. This is where you will add the modules and interconnect them and see the flow of data. The data flows down the module creation modules down to the viewer. The leaching monitoring application is shown in the following section.
6. On the very right is the Properties window where you can set the parameters for each module. You can set module properties by double-clicking on any module (or connection) in your Application.

3.2. EVS Modules for Leaching

The application window for the SPR leaching is shown in Figure 3-2. There is a total of 28 modules. The module types and their descriptions are in Table 3-1. A module's default name is its module type but can be renamed. The `load_evs_field` and `slice` modules were renamed to make it easier to find a specific object. Most modules in the application have input and output ports. These are the colored regions (ports) on the modules, representing the pipelines through which data flows to and from each module (C Tech, 2021). Every port has a different function for each module, but blue connections generally communicate the file's data and red connections visualize the renderings into the viewer.

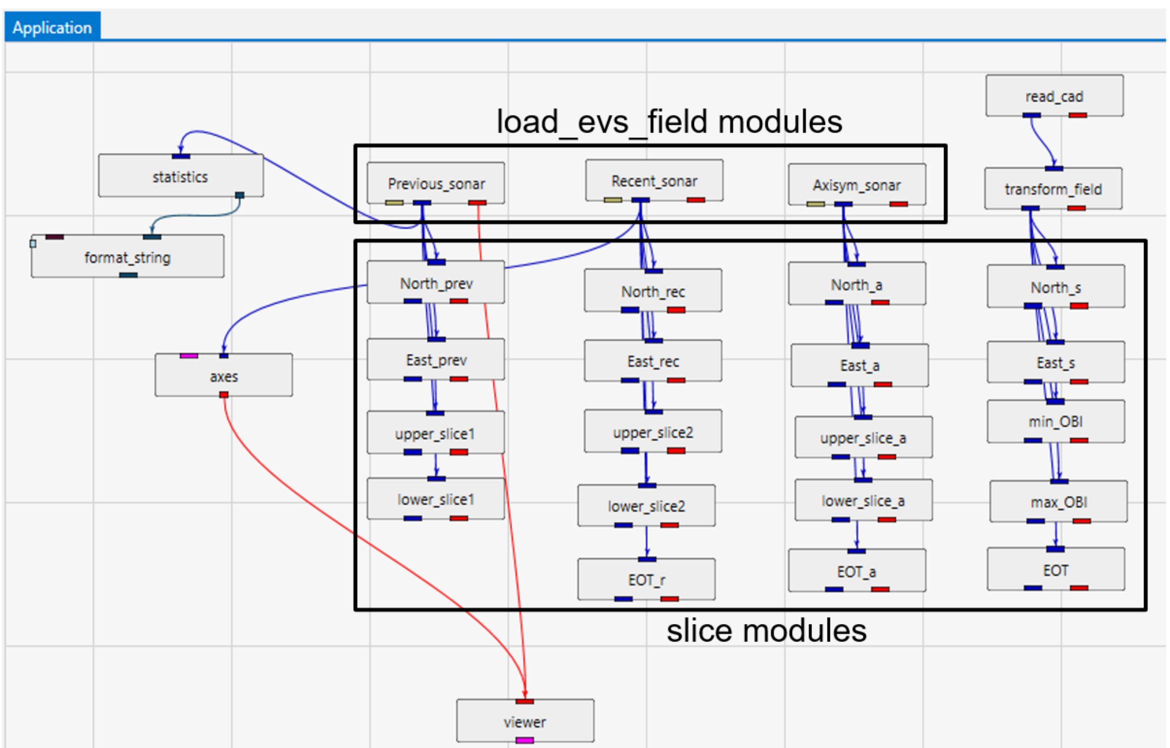

Figure 3-2. EVS leaching application window

Table 3-1. EVS Modules and Descriptions

Module Type	Description*
`load_evs_field`	Reads a dataset from any six different EVS compatible file formats into an EVS field
`axes`	Places 3D axes in the viewer scales by the model data and/or user defined limits
`statistics`	Analyzes the statistical distribution of a single data from a field
`format_string`	Provides a simple means to convert values coming from various numeric and sting input ports into a resultant string
`slice`	Creates a subset of your input which is of reduced dimensionality
`read_cad`	Reads all versions of AutoCAD DWG and DXF files
`transform_field`	Translates, rotates, or scales the coordinates any field
`viewer`	Displays all 3D models
*All module descriptions come from Earth Volumetric Studio Enterprise Version 2021.4.3.	

3.2.1. Load_evs_field and Read_cad

In the `load_evs_field` module, the sonar is uploaded using a .eff file. There are three modules: the recent sonar, the previous sonar, and the axisymmetric representation of the recent sonar. The .eff file reports depths, distances, and volumes from the sonar. EVS extrapolates and interpolates the data and creates nodes and cells that can present the data visually. The many nodes that make up the sonar allow a color gradient to be used at different depths for the sonar. In the `read_cad` module, the SANSMIC model output is uploaded using a .dxf file, which can be generated from SANSMIC output by the CloudCompare software (Cloud Compare, 2021). There is only one `read_cad` model for the SANSMIC output for the leaching results for that CY. The .dxf file transforms the SANSMIC output into a computer-aided design object that can be imported into the EVS field. The SANSMIC output can only be shown as one color because it is imported as a single object into EVS.

3.2.2. Axes

The `axes` module is used to place 3D axes in the viewer. The `axes` can be scaled by the model data or defined by user limits in the x,y,z coordinates, but first, the `axes` need a field input to position and scale the axes to that EVS field. Any `load_evs_field` modules are acceptable inputs for the `axes` module since they all use the same well coordinates. Like other objects in the viewer, `axes` are transformable and can be changed through the properties tab. The `axes`' parameters are set before any plots are exported and do not change from plot to plot. Most of the settings for the `axes` parameters are assigned to the default values. The settings modified for leaching monitoring plots under the spatial definition parameter are the interval spacing for the x, y, and z coordinates shown in the blue box in Figure 3-3. In general properties, the object color is changed to a darker shade of white, shown by the blue arrow in Figure 3-4. Lastly, the display settings that are changed from their default are highlighted with blue arrows in Figure 3-5.

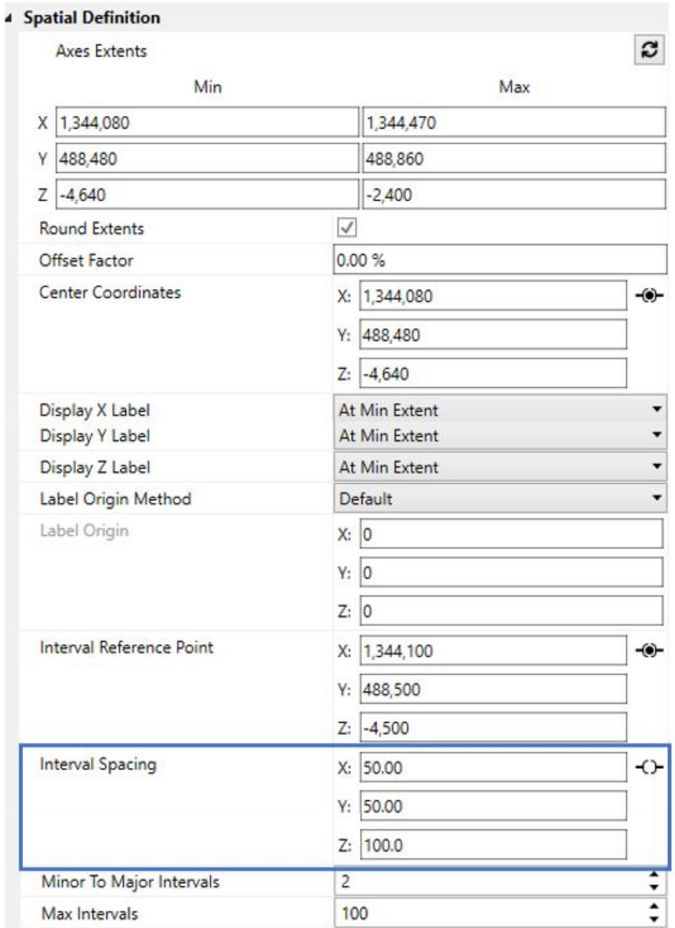

Figure 3-3. Interval spacing parameter for axes module

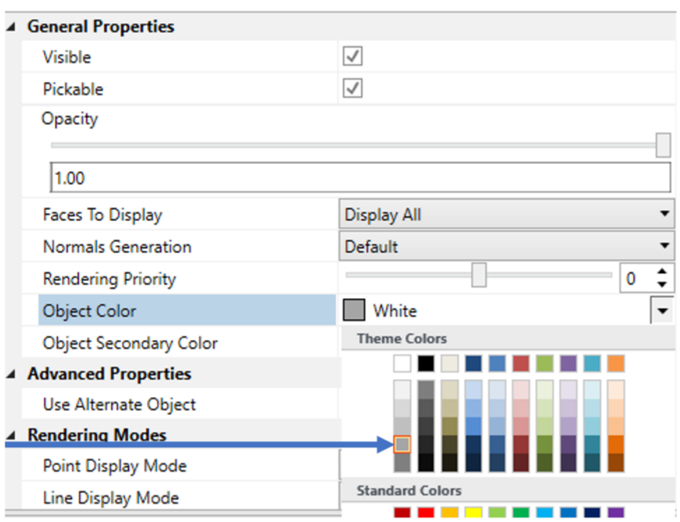

Figure 3-4. Object color for axes module

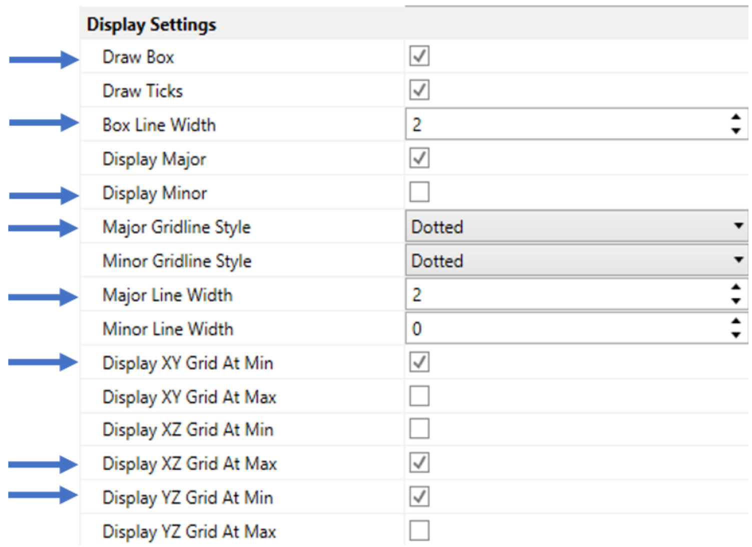

Figure 3-5. Display settings for axes module

3.2.3. Slice Type- Northing, Easting, and Horizontal

As discussed in Section 2, the two cross-sections used in leaching monitoring are vertical and lateral and the `slice` module is used to visualize them. In EVS, there are two slice types for the vertical cross-section and one slice type for the horizontal cross-section. The two types of slices for the vertical cross-sections are the northing and easting slices defined by the y and x coordinate, respectively. The x and y coordinates are the well coordinates from the sonar, located in the sonar's metadata section. Each object used for leaching monitoring has one northing and one easting slice. These slices are renamed with a "North" or "East" prefix in the application window. The slice type for the lateral cross-section is the horizontal slice. The horizontal slice type is defined by the z coordinate, which corresponds to the depth of interest for each plot type. Depending on the plot type, there are two to three horizontal slices for each object and are renamed with the depth of interest as the prefix in the application window. Figure 3-6 shows where to change the slice type in the parameters window for the slice module.

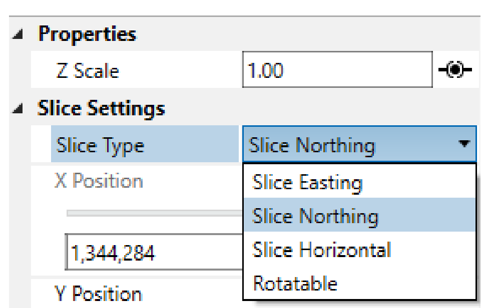

Figure 3-6. Slice type settings for slice module

4. AUTOMATION OF PLOT GENERATION: METHODOLOGY FOR PYTHON SCRIPT

The automation of the leaching plots was done using the Python scripting function within EVS. The leaching history plots, axisymmetric plots, and SANSMIC plots discussed in Section 2 were produced using one script. The script consists of five main sections spanning over 3,000 lines of code and currently has a run time of approximately one hour for producing 624 plots total for 24 caverns. The script was created in Earth Volumetric Studio version 2021.4.3, which uses Python 3.9. EVS is only installable on a windows system and is required to run the script. The script filename is "leaching_2021.py" and is currently located in SNL's SPRDATA drive under the following file path: S:\Task-2\Subtask-2.4\Plots\EVS_Python\Full Script and References\leaching_2021.py. A brief overview of the layout for the code can be seen in Table 4-1.

Table 4-1. Overview of script structure

Section	Function
Libraries	Import evs, evs_until, datetime, os, os.path
Dictionaries	Slice depths of intertest, final and initial OBIs, and EOTs for each cavern Scale for each SPR site
File paths	Accesses folder/file paths to import sonar, axisymmetric, and SANSMIC files
Functions	Predefined functions to be referenced and utilized throughout the script
Separate loops for each cavern	Runs through each cavern, outputting 26 .png plots per cavern Calls on several predefined functions, adjusts EVS module connections, and resets before entering new cavern files

4.1. Script Structure

The first section, which only takes up a couple of lines at the beginning of the script, covers the five libraries that need to be imported for to run properly. Table 4-2 lists the five Python libraries and their function in the EVS/Python scripting space. The first three listed are automatically imported when opening a new Python script in EVS, and the other two must be imported manually. The os and os.path libraries have been imported manually to access the necessary files and file path names from their designated folder.

Table 4-2. Leaching Python script's libraries and functions

Python library	Function
evs	Compatibility with the EVS interface
evs_util	EVS module types and settings
datetime	Basic date and time types
os	Miscellaneous operating system interfaces
os.path	Common pathname manipulations

The second section serves as a collection of dictionaries. The purpose of these dictionaries is to store data and measurements to be used throughout the script. There are 31 different dictionaries containing slice depths for each type of plot and scaling factors for each of the four SPR sites. As discussed in Section 2 of this report, there are several different depth measurements needed to create the leaching plots for each cavern. Each dictionary in the script holds the most recent data for these measurements, which are specific to each cavern. These include upper and lower slice depths, EOT depths, and minimum and maximum OBI depths—all of these values are user-specified, vary for each cavern, and must be updated for each leaching year. Figure 4-1 shows a section of dictionaries within the code, used to store the depths needed for leaching history plots and axisymmetric plots.

```
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
                            Dictionaries for slice depths
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

# All plots
Scale = {"BC":0.4,"BH":0.26,"BM":0.26,"WH":0.26}
# Leaching History Plots- these plots should show how much leaching has occured through the previous and most recent sonar (hence, these depths
# Hupper- first depth of interest in leaching history figure, Hlower-second depth of interest in leaching history figure
BC_Hupper = {"BC-018X":-3800}
BC_Hlower = {"BC-018X":-4100}
BH_Hupper = {"BH-101A":-3800,"BH-102A":-3700, "BH-104A":-4000,"BH-105A":-3750,"BH-107A":-3900,"BH-108A":-3050,"BH-109A":-3900,"BH-110A":-3900,"B
BH_Hlower = {"BH-101A":-4050,"BH-102A":-3950, "BH-104A":-4115,"BH-105A":-3950,"BH-107A":-4020,"BH-108A":-4000,"BH-109A":-4100,"BH-110A":-4100,"B
BM_Hupper = {"BM-004A":-2600,"BM-105B":-4000,"BM-106B":-3550,"BM-113A":-2600,"BM-114A":-3800,"BM-116A":-3300}
BM_Hlower = {"BM-004A":-3050,"BM-105B":-4150,"BM-106B":-3700,"BM-113A":-3225,"BM-114A":-4075,"BM-116A":-4015}
WH_Hupper = {"WH-011S":-3600,"WH-109X":-4300,"WH-111X":-4100,"WH-112X":-4300,"WH-114X":-4200,"WH-115X":-4000,"WH-117A":-3550}
WH_Hlower = {"WH-011S":-3700,"WH-109X":-4500,"WH-111X":-4400,"WH-112X":-4475,"WH-114X":-4450,"WH-115X":-4550,"WH-117A":-4500}
# Axisymmetric Plots- these depths should show how much ovality this cavern exhibits
# asymupper- first depth of interest in axisymmetric comparison figure, asmlower-second depth of interest in axisymmetric comparison figure
BC_asymupper = {"BC-018X":-3800}
BC_asymlower = {"BC-018X":-4100}
BH_asymupper = {"BH-101A": -3800,"BH-102A":-3700, "BH-104A":-4000,"BH-105A":-3750,"BH-107A":-3900,"BH-108A":-3050,"BH-109A":-3900,"BH-110A":-39
BH_asymlower= {"BH-101A":-4000,"BH-102A":-3950, "BH-104A":-4115,"BH-105A":-3950,"BH-107A":-4020,"BH-108A":-4000,"BH-109A":-4100,"BH-110A":-4100,
BM_asymupper = {"BM-004A":-2600,"BM-105B":-4000,"BM-106B":-3550,"BM-113A":-2600,"BM-114A":-3800,"BM-116A":-3300}
BM_asymlower= {"BM-004A":-3050,"BM-105B":-4150,"BM-106B":-3700,"BM-113A":-3225,"BM-114A":-4075,"BM-116A":-4015}
WH_asymupper = {"WH-011S":-3600,"WH-109X":-4300,"WH-111X":-4100,"WH-112X":-4300,"WH-114X":-4200,"WH-115X":-4000,"WH-117A":-3550}
WH_asymlower= {"WH-011S":-3700,"WH-109X":-4500,"WH-111X":-4400,"WH-112X":-4475,"WH-114X":-4450,"WH-115X":-4550,"WH-117A":-4500}
```

Figure 4-1. Dictionaries containing slice depths for each cavern

The third section contains several variables which hold the file paths and file directories needed to create the leaching plots. There are separate folders for previous sonars, recent sonars, axisymmetric sonars, and SANSMIC files for each site. The folder path directories containing the sonar and SANSMIC files have been embedded directly into the script. They are then used to create a list of all the files within each folder. These lists make it possible to loop through all of the files for each SPR site later in the script. Figure 4-2 includes a section of code with the file paths and file directories for Bayou Choctaw.

```
# Bayou Chactow

# previous sonar
BC_folderpath_prev = r"S:\Task-2\Subtask-2.4\Plots\EVS_Python\2020 Leaching Files\BC\Previous Sonars"
BC_filepaths_prev = [os.path.join(BC_folderpath_prev, name) for name in os.listdir(BC_folderpath_prev)]
# recent sonar
BC_folderpath_rec = r"S:\Task-2\Subtask-2.4\Plots\EVS_Python\2020 Leaching Files\BC\Recent Sonars"
BC_filepaths_rec = [os.path.join(BC_folderpath_rec, name) for name in os.listdir(BC_folderpath_rec)]
# recent axisymmetric sonar
BC_folderpath_Axi_rec = r"S:\Task-2\Subtask-2.4\Plots\EVS_Python\2020 Leaching Files\BC\Axisymmetric Sonars"
BC_filepaths_Axi_rec = [os.path.join(BC_folderpath_Axi_rec, name) for name in os.listdir(BC_folderpath_Axi_rec)]
# sansmic
BC_folderpath_sans = r"S:\Task-2\Subtask-2.4\Plots\EVS_Python\2020 Leaching Files\BC\SANSMIC Files"
BC_filepaths_sans = [os.path.join(BC_folderpath_sans, name) for name in os.listdir(BC_folderpath_sans)]
```

Figure 4-2. Lists of folder paths for Bayou Choctaw

The fourth section defines functions to be used throughout the script. The purpose of these functions is to find a corresponding SANSMIC file for any cavern that has been loaded into EVS. Four total functions match the SANSMIC file, one for each site. Figure 4-3 shows the SANSMIC file name function for BC. The purpose of the fifth function is to adjust the extents of the cavern axes and is utilized to make sure the cavern is properly aligned before outputting the .png images for each leaching plot. When a sonar is uploaded into an EVS field, the axes fit the sonar's maximum and minimum extents. A padding of 40 ft was added to the sides and bottom of the cavern to provide additional space on each side of the sonar, shown in Figure 4-4.

```
def BC_Get_Sansmic_file(well_name):
    
    ''' This function gives the correct file path for the matching SANSMIC file, given the well name '''
    
    for s in BC_filepaths_sans:
        simplewn = well_name[:]
        # print(simplewn)
        sanwelln = s[76:82]
        # print(sanwelln)
        sanwell = sanwelln[:2]+ "-" + sanwelln[2:6]
        # print(sanwell)
        if sanwell == simplewn:
            swellname = sanwell
            print(swellname)
            return (s)
```

Figure 4-3. SANSMIC file name function for BC

```
def adjust_extents():
    
    ''' This function adjusts the axis extents to give 40 ft of space on each side (excluding top) '''
    
    global axesextents
    evs.set_module('axes', 'Spatial Definition', 'Axes Extents', {'Linked': True})
    axesextents = evs.get_module('axes', 'Spatial Definition', 'Axes Extents')
    #print(axesextents)
    newminx = axesextents['MinX']-40
    newminy = axesextents['MinY']-40
    newminz = axesextents['MinZ']-40
    newmaxx = axesextents['MaxX']+40
    newmaxy = axesextents['MaxY']+40
    newmaxz = axesextents['MaxZ']
    evs.set_module('axes', 'Spatial Definition', 'Axes Extents', 
                    {'MinX': newminx, 'MaxX': newmaxx, 'MinY': newminy, 'MaxY': newmaxy, 'MinZ': newminz, 'MaxZ': newmaxz, 'Linked': False})
    axesextents = evs.get_module('axes', 'Spatial Definition', 'Axes Extents')
```

Figure 4-4. Axes extents adjustment function for all sites

The fifth section makes up the largest portion of the code and is comprised of several loops. Each site within the SPR has its own loop that creates the necessary leaching plots for all the caverns within that site. Each of the four main loops follows the same structure and is set up to run through one cavern at a time. The script creates all 26 plots for a single cavern before moving on to the following file, going through each cavern individually. The code is designed to loop through each sonar placed in the "Recent Sonars" folder. The well name is extracted from the recent sonar file name and is used to find the file in the "Previous Sonars" folder with the same well name. After the corresponding recent and previous sonars for a particular well are identified, they are loaded into the EVS module setup discussed in Section 3. After accessing the file notes to extract the well name and cavern extents, the slice depths are then pulled from the corresponding dictionary to be entered into the EVS slice module. Next, the leaching history plots are created using the Python notation for all the necessary EVS module adjustments and saved as .png files. A nested loop is then utilized to find the corresponding axisymmetric file by extracting the well name from the recent and axisymmetric sonar file paths and identifying the axisymmetric file that matches the recent sonar. Then the axisymmetric plots are created following a similar process. Finally, the script uses one of the predefined functions to find the corresponding SANSMIC file. The SANSMIC file and the leaching history sonars and axisymmetric sonar create and output all the SANSMIC plots. This process is repeated for every cavern within the site of the main loop. After every cavern within that site has been accounted for and plots have been created, the script moves on to the next SPR Site. Figure 4-5 includes a section of code with beginning of the main loop for Bayou Choctaw.

```
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
                        Bayou Choctaw Leaching History Figures
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
# Includes 9 plots total
# (4) leaching history- previous and current sonar vertical north and west
# (2) leaching history- vertical outline comparing previous & recent north and west
# (3) leaching history- horizontal cross sections (at depth 1, depth 2, and depth 1 + depth 2)

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
###############################################################################################

for r in BC_filepaths_rec:

    evs.set_module('Recent_sonar', 'Properties', 'Filename', r)                                #
    evs.set_module('Recent_sonar', 'Properties', 'Execute', True)
    rwellname = r[-11:]                                                                        #
    print(r[-11:])
    # get xmin, xmax, ymin, ymax, zmin, zmax coordinates for axis
    # get lccs (well coordinates)

    def FileNotesDict(filenotes):
        filenotes = filenotes[0:-2]                                                            #
        notelist = filenotes.split("\n")                                                       #
        notedict = {note.split(':')[0] : note.split(':')[1] for note in notelist}              #
        return (notedict)

    def GetEFFStats(statstr):
        """
        pull XYZ extent information from statistics module string
        return the XYZ values as individual dictionaries
        """
        statstr = statstr.replace(':','')                                                      #
        statslist = statstr.split('\n')                                                        #
        spacelist = [s for s in statslist if 'Extent' in s]                                    #

        xspacelist = spacelist[0].split('\t')
        yspacelist = spacelist[1].split('\t')
        zspacelist = spacelist[2].split('\t')

        xspacedict = {xspacelist[i]: float(xspacelist[i+1]) for i in range(0, len(xspacelist),2)}
        yspacedict = {yspacelist[i]: float(yspacelist[i+1]) for i in range(0, len(yspacelist),2)}
        zspacedict = {zspacelist[i]: float(zspacelist[i+1]) for i in range(0, len(zspacelist),2)}

        return(xspacedict, yspacedict, zspacedict)
```

Figure 4-5. Beginning of Bayou Choctaw loop to generate plots

4.2. Folder Path Structure and Naming Conventions

There is a specific setup for both the folders and file paths for the script to run through the caverns in an organized manner. An overview of the setup for the 2020 leaching folder can be seen in Figure 4-6. There are four main folders titled “BH,” “BC,” “BM,” and “WH.” Each folder contains all the files and leaching plots for each site. Within each site-specific folder, there are seven sub-folders, as seen in Figure 4-7. The first four sub-folders, “Previous Sonars,” “Recent Sonars,” “Axisymmetric Sonars,” and “SANSMIC Files,” contain the files needed to create the leaching plots. The remaining three sub-folders, “Leaching History Plots,” “Axisym Plots,” and “SANSMIC Plots,” are where the images for each leaching plot are written to. Before running the script for the first time, all three of the 'Plots' folders should be empty.

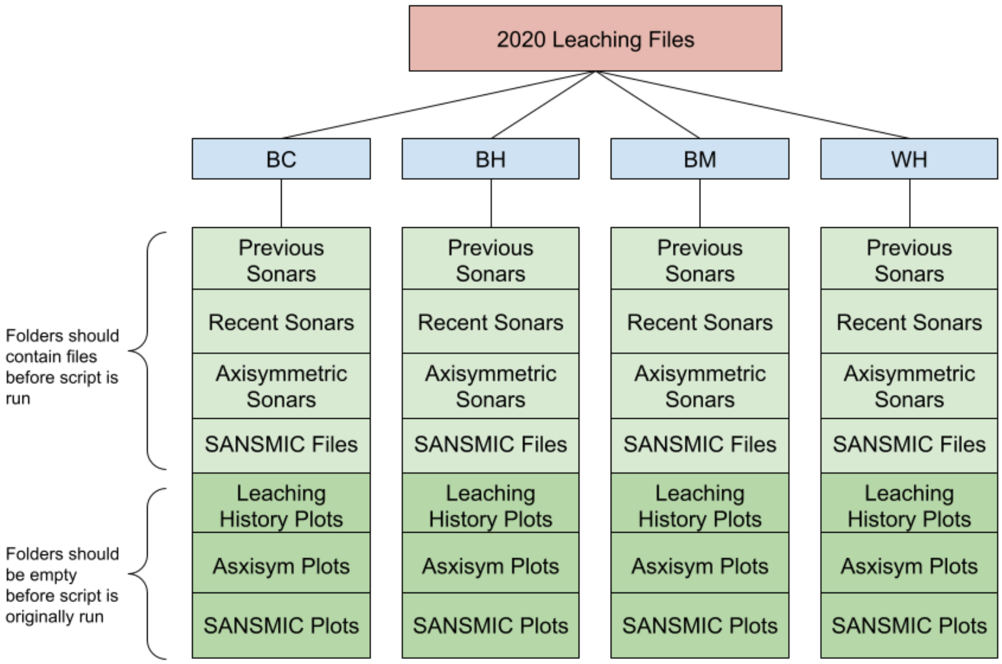

Figure 4-6. Overview of 2020 leaching files folder setup

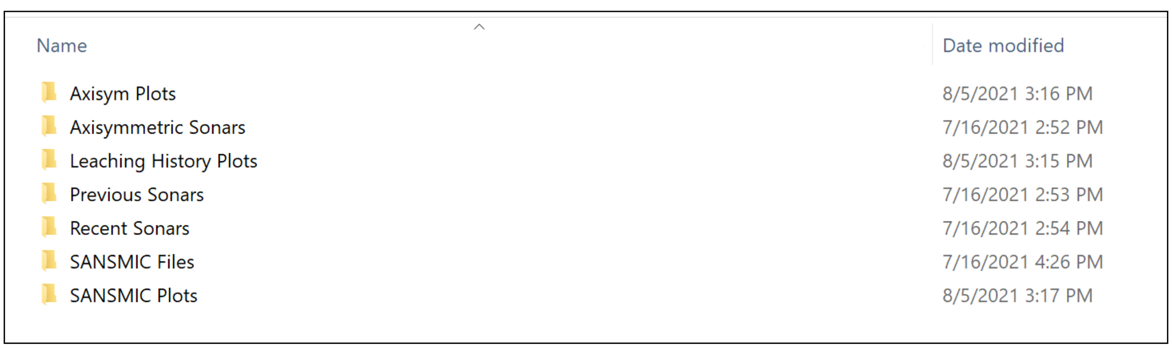

Figure 4-7. Folder setup for each site

For the script to run properly, several naming conventions must be followed. This includes both file names and the names of dictionary keys within the script. A summary of these naming conventions can be seen in Table 4-3.

Table 4-3. File naming conventions, shown for BC-18

File/Variable Type	File/Variable Name
Dictionary key names	"BC-018X"
Previous and recent sonar eff file notes	"BC-018X"
Previous sonar	"BC018_2018-01-09_BC-018X.eff"
Recent sonar	"BC018_2020-12-29_BC-018X.eff"
Axisymmetric sonar	"BC018_2020-12-29_BC-018X_axisym.eff"
SANSMIC file	"BC018X_vertices.dxf"

The two-letter cavern site code should be listed for dictionary elements representing a specific cavern, followed by a dash and the well code. In the case that there is no "A" or "B" well code, the letter "X" should be put in as a placeholder, as seen in the Bayou Choctaw example in the table. Each of the files should also follow the same naming convention seen in the table. The last seven characters should consist of a cavern code and well code for the previous and recent sonars, separated by a dash. Similar to the dictionary key, if there is no specific well code such as "A" or "B," then an "X" should be put in as a placeholder. The axisymmetric sonar should be the same as the Previous Sonar and Recent Sonar filenames with the addition of "_axisym" at the end of the file name. The SANSMIC file should have the two-letter cavern site code, the well code, and "_vertices.dxf". The last important naming convention is within the EFF file notes for the recent and previous sonars. Under the well-code section of the EFF file notes (highlighted in Figure 4-8), the name should have the two-letter cavern site code followed by the well code. This should match the dictionary key name for the cavern. Table 4-3 is a good reference for all of the naming conventions currently being used for each file.

```
DATE_CREATED 2021-01-15 10:34:57.884319

EVS_FIELD_FILE_NOTES_START

CAV: BC018
WELL: BC-018X
DATE: 2020-12-29
LCCS: <2008485.5, 599475.3>
BHF:  <13.5>
```

Figure 4-8. EFF file notes with proper naming conventions

4.3. Script Functions for Future Usability

Although the script runs through each cavern in the dictionaries to create the plots in one continuous process, some things need to be considered before running the script. The first thing that needs to be done is to update the dictionary section of the code with the current depths of each slice. This includes upper and lower slice depths, EOT depths, and minimum and maximum OBI depths. Each site has its own set of dictionaries for slice depths. A new entry must be added following the same naming conventions discussed earlier if a specific cavern is not listed within a site dictionary. There is also a dictionary containing the scale used to view each cavern before outputting the plots. The current scale numbers can fit all of the caverns created for the 2020 cavern leaching year. The scales are site-specific, so if there is an issue with a scale being too zoomed in/out, then these numbers may have to be adjusted in the future. Because the file path section of code uses specific file path addresses to access each file, if the folder path structure is changed from the current format listed earlier, then the code needs to be updated. This would include changing the folder paths listed for each site in the folder/file section of the code and changing the file paths that the .png images are being written to in each loop so that new images are being sent to the correct location within the new folders.

4.4. Future Capabilities and Limitations

Currently, the script can create leaching plots if there is one EOT depth and the previous and recent sonars were run down the same well. If a cavern has two EOT depths in a single leaching period, then the horizontal and vertical cross-sections, discussed in the SANSMIC figure section, need to be done manually. Lastly, the current script cannot compare two sonars taken down different wells due to the the x and y coordinates misalignment. Comparing two sonars taken down different wells is not common but is still something that has occurred in previous leaching years, so it is an important case to note. Although the script is not currently set up to work with two sonars from different wells or, in the case of two EOT depths, these functionalities could be implemented in the future. The script generates all of the plots as separate .png files, so putting the plots together into a figure (such as Figure 2-1) is a process that is done manually through PowerPoint. The assembly of the plots into a single figure is not part of the automated process. This is another functionality that could be implemented in the future. All Python scripting and EVS capabilities used to automate the leaching plots are compatible with Earth Volumetric Studio 2021.4.3 and Python 3.9. If future EVS updates include changes to module syntax, the script will need to be updated accordingly.

5. CONCLUSIONS

This report identifies the plots needed for the Leaching Figures used in the annual Cavern Leaching Monitoring Reports and the efforts to automate this process. The Cavern Leaching Monitoring Reports investigate the impacts of sales operations on the long-term integrity of the caverns from raw water leaching. Three main Leaching Figures are used to visualize volume and shape change using the most recent and previous sonar surveys and SANSMIC model leaching predictions. For each cavern leached in a calendar year, the three figures are:

- The leaching history.
- A comparison of the axisymmetric representation and the most recent sonar.
- A comparison of the SANSMIC prediction to the most recent sonar and its axisymmetric representation.

The automation of the leaching plots was done using the Python scripting function within EVS software. There are 26 subplots produced for each cavern to compose the three figures mentioned above, and their descriptions are summarized in Table 5-1. The current script comprises more than 3,000 lines of code and loops through all four sites in the SPR. Most subplots require predetermined depths of interest to be embedded in the script's dictionaries, so the process is not fully automated. However, the current run time for the script is one hour, replacing 40-50 hours of the monitoring cavern leaching process that can be automated. After the subplots are created, the figures are assembled in PowerPoint manually. Currently, there is no automation process for the assembly of subplots, but it can be a functionality explored in the future.

Table 5-1. Summary of Plots for Leaching Figures

Subplot description	# of subplots	Automated?
Vertical profiles of the most recent and previous sonars (north and west)	4	Yes
Vertical cross-section comparing the most recent and previous sonars (north and west)	2	Partially- need depth(s) of interest for horizontal reference lines
Lateral cross-sections at depth(s) of interest	3	Partially- need depth(s) of interest for each cross-section
Vertical profile of recent sonar- solid blue (north and west)	2	Yes
Vertical profile of axisymmetric representation- solid orange (north and west)	2	Yes
Vertical cross-section comparing recent sonars and axisymmetric (north & west)	2	Partially- need depth(s) of interest for horizontal reference lines
Lateral cross-sections at depth(s) of interest	3	Partially- need depth(s) of interest for each cross-section
SANSMIC prediction- vertical north & west	2	Yes
SANSMIC prediction- vertical outline comparing sonar & axisymmetric north & west	2	Partially- need OBI-f, OBI-I, and EOT for horizontal reference lines

Subplot description	# of subplots	Automated?
SANSMIC prediction- Horizontal cross sections (OBI-f, OBI-I, EOT)	3	Partially- need OBI-f, OBI-I, and EOT depths for each cross-section
SANSMIC Prediction- side profiles of sonar outline comparing most recent sonar & axisymmetric with no axes	1	Partially- need OBI-f, OBI-I, and EOT for horizontal reference lines
Total:	26	Script run time: 1 hour

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