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Advanced CO2 Storage Capacity Estimation with EASiTool V.5

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Abstract

Geological storage of anthropogenic CO2 plays a pivotal role in Carbon Capture and Storage (CCS) projects. The initial stages of site screening, site selection, and storage capacity estimation are crucial for project commencement. Additionally, in the context of class VI permit applications, accurate assessments of reservoir-scale pressure build-up and CO2 plume dimensions during the injection phase are vital. The Enhanced Analytical Simulation Tool (EASiTool) is a versatile platform designed to support the science-based estimation of CO2 storage capacity for Geological Carbon Storage (GCS). It offers a wide range of powerful features to facilitate efficient and precise CO2 storage simulation and estimation. The latest version, EASiTool version 5.0, introduces substantial updates and advantages through its modern, web-based interface, surpassing its previous versions.

EASiTool comprises two primary modules, each tailored to distinct scenarios and reservoir geometries: User-Given Inputs, and Maximum Storage Capacity. These modules cater to potential project sites with predefined injection scenarios and geometries, or general injection estimates based on reservoir characteristics, such as maximum injection pressure. Both modules generate pressure contour maps and CO2 plume extension maps after the injection phase.

Furthermore, EASiTool now includes Geographic Information System (GIS) maps, probability assessments for the Area of Review (AOR), enhanced sensitivity analysis using Monte Carlo Simulation, and the evaluation of storage efficiency factors as new additions. For boundary conditions, the new version leverages analytical models for closed-, or open-boundary basins, and accounting for natural faults. This tool empowers users to obtain optimized storage capacity estimates and injection scenarios, typically delivering results within seconds. The Net Present Value (NPV) model has also been updated to provide a more realistic financial evaluation. The powerful functionalities offered by EASiTool foster a comprehensive decision-making approach, ensuring that choices are based on robust scientific findings. This, in turn, enables a more effective and successful implementation of carbon storage initiatives.

Introduction

Geological storage of captured CO2 from industrial sources aims to mitigate atmospheric emissions. However, CO2 injection leads to increased pressure in the storage formation (Nicot, 2008), as a critical concern impacting storage capacity and injectivity. Pressure interference, as well as the influence of boundary conditions, will shape final pressure distribution and injectivity. Managing formation pressure involves both estimating final pressure distribution and preventing pressure buildup beyond allowable limits (Mathias et al., 2009; Rutqvist et al., 2008), to create the pressure space to allow CO_2 geological storage (Kim & Hosseini, 2014; Bump et al., 2023).

While commercial numerical simulators can accurately simulate Geological Carbon Storage (GCS) projects, they are time-consuming, expensive, and require highly skilled individuals (Ganjdanesh and Hosseini, 2018). In contrast, simple methodologies for calculating storage capacities, as outlined in an EPA carbon sequestration report, lean on static formation properties and an empirical storage efficiency factor. Volumetric methods proposed by the Carbon Sequestration Leadership Forum method (CSLF, 2008), the University of North Dakota Energy & Environmental Research Center (Gorecki et al., 2009), DOE/NETL (NETL, 2010), and USGS (Brennan et al., 2010) offer ways to estimate storage resource potential. However, as pointed out by Treviño & Meckel (2017) and Bump et al., (2023), these predictions are based on storage zone static parameters, which are idealized, and maximum values, and more accurate dynamic estimation based on injectivity, and site-specific information should be provided instead.

Emerging integrated tools, such as InfraCCS (Morbee et al. 2011), and MARKAL-NL-UU toolboxes (van den Broek et al. 2010), address CO2 storage estimation challenges but sometimes have limitations when confronting geological assessments, complex geometries, and leakage evaluations. Middleton et al. (2020a&b) introduced SCO2T, a rapid tool for carbon sequestration science, engineering, and economics. Developed in Microsoft Excel VBA for broad accessibility and ease of use, SCO2T excels in performing numerous simulations rapidly, facilitating sensitivity and uncertainty analysis related to storage estimation. Despite its strengths, SCO2T has limitations, assuming reservoir homogeneity and overlooking factors like leakage, reservoir fluid composition, and pressure interference between injection wells. (Ma et al. 2023, Leng et al., 2024).

EASiTool was initially developed by Ganjdanesh and Hosseini (2017, 2018), and has recently undergone updates and transitioned into a web-app environment as version 5.0 (Wang & Hosseini, 2023). EASiTool is a robust toolbox designed to assess the storage capacity of geological formations suitable for CO2 sequestration, and aid in the selection and filtering of potential geological sites. Functioning as an enhanced analytical simulation tool. The toolbox incorporates the pressure space concept (Bump et al., 2023) in CO2 geological storage (CGS), enhancing the accuracy of dynamic storage capacity assessments during injection compared to static storage capacity calculations (Leng et al., 2024). EASiTool can also effectively manage in-situ brine and controls pressure build-up by integrating CO2 injection and brine extraction processes.

This work features the functionality of the newest version 5.0 of EASiTool. Compared to the last version 4.0, the newest version is fully web-based and developed in a Python environment with an improved UI/UX design. It utilizes the integrated Excel input file. Two modules, user-given input, and max storage capacity, correspond to a mature project with well/reservoir location and injectivity or a more primitive project during the site-selection stage. Moreover, the newly featured Area of Review (AoR) and GIS map visualization also further facilitate project decision-making.

Methodology

EASiTool is based on an analytical model, the reservoir and wells model used follows the following assumptions. 1. Reservoirs are considered homogeneous and reservoir properties are isotropic, and the top and bottom are closed; 2. all the wells are fully penetrating, vertical wells; 3. during the injection process, the injection and extraction (if any) rates are constant; 4. all the reservoir boundaries are either all open (permeable) or all closed. For the flow model, EASiTool assumes 1D radial flow, multiphase fluid of CO_2 and brine (Mathias et al., 2011a; Pooladi-Darvish et al., 2011). Such fluids are assumed to be slightly compressible with constant compressibility and viscosity. Brine density and viscosity are calculated using the Rowe-Chou (Rowe and Chou, 1970) and Kestin (Kestin et al., 1981) methods, while the mutual solubilities between CO_2 and aqueous phase are calculated by the Spycher method (Spycher et al., 2003).

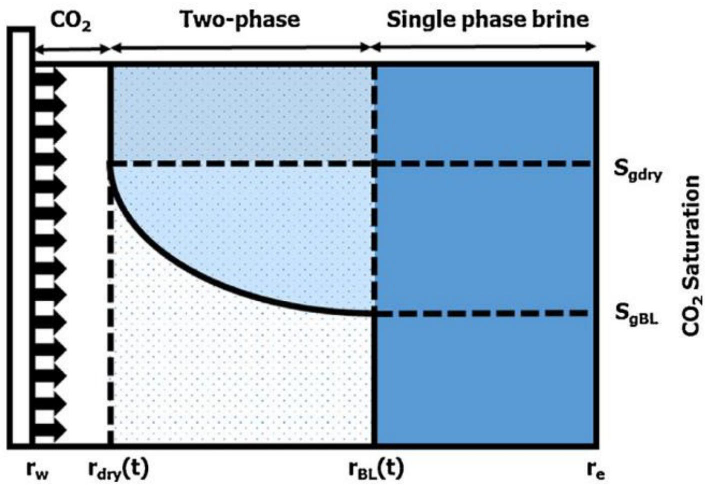

Figure 1 Diagram of the one-dimensional flow of CO2 and brine through fully penetrating vertical wells, forming three sections: dry-out region, middle region, and single-phase brine region. r_{dry}, r_{BL} and r_e denote the radii of these three regions (McMillan et al., 2008)

The diagram illustrates the three CO_2 plume flow regions around the wellbore as shown in Figure 1. Three regions, the dry-out region (single-phase CO_2), the middle region (two-phase, saturated CO_2 dissolved in aqueous phase), and the single-phase aqueous region, are formed near the fully penetrated vertical injection wells. r_{dry}, r_{BL} and r_e denote the locations separate these three regions, and the value of r_{dry} and r_{BL} are calculated by Buckley-Leverett type of method (Buckley & Leverett, 1942; Azizi & Cinar, 2013a, 2013b; Mathias et al., 2011a, 2011b)

The analytical model (Azizi & Cinar, 2013a, 2013b) was implemented to measure the pressure buildup and drawdown due to CO_2 injection (and/or brine extraction). This method utilizes the superposition technique to predict the ultimate pressure distribution within the reservoirs after the injection period. Ganjdanesh and Hosseini (2018) explained the derivation of final normalized pressure distribution under both open and closed boundary conditions. By rearranging the dimensionless pressure distribution into matrix form, the following equation can be derived.

$$\bar{\bar{A}}\bar{Q}=\bar{B}$$

$\bar{\bar{A}}$ is a matrix, comprising intermediate coefficients of each well. The coefficients encompass both injection and extraction wells and are intricately linked to the properties of multiphase fluid flow, dimensionless time, the locations of individual wells, well skins, and other relevant factors (Ganjdanesh & Hosseini, 2018).

$\bar{Q}$ and $\bar{B}$ are vectors, which are related to flow rates and pressure differences between maximum allowable injection pressure and initial reservoir pressure (or minimum pressure) respectively. By providing values of either flow rates or the initial and fracture pressure of the reservoir, either the final pressure distribution or flow rates can be calculated.

Demonstration and case study

The new version features the web-app environment. It provides a toolbox to effectively evaluate geological CO2 storage projects. In this section its user interface will be briefly described, then a case study will be demonstrated.

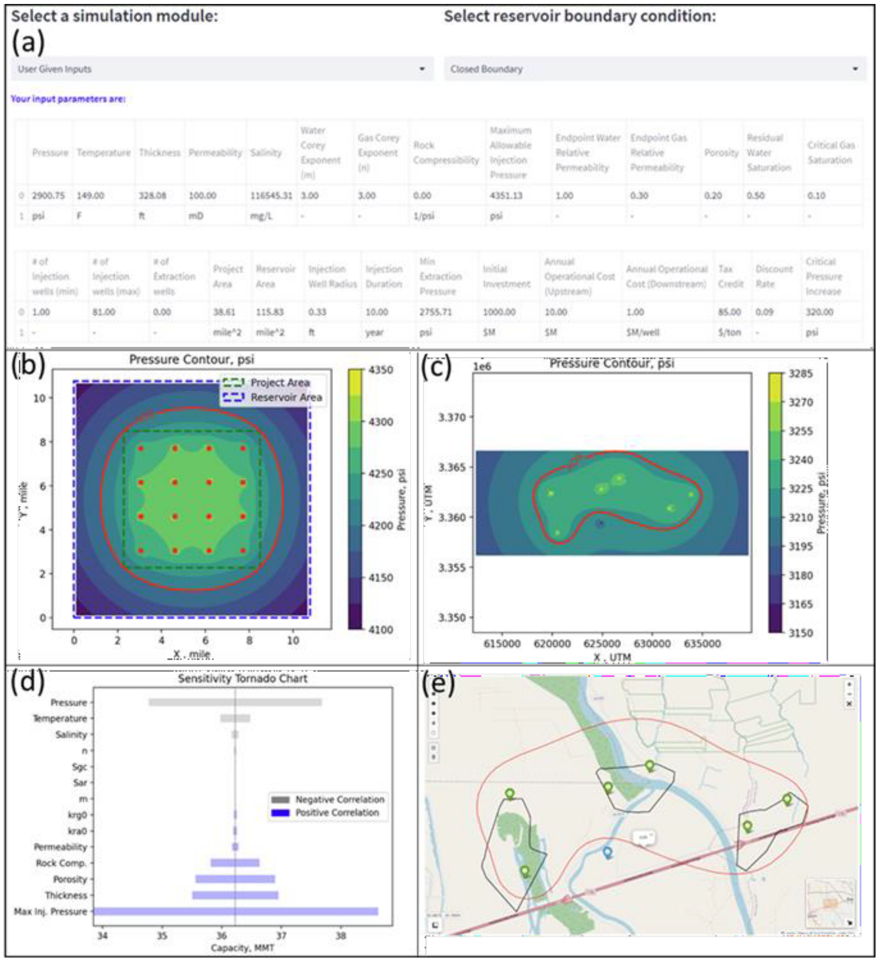

Figure 2 Screenshot of EASiTool V5.0 user interface (image courtesy: Dr. Jianqiao Leng)

1. User interface:

Figure 2 illustrates various aspects of EASiTool V5.0 functionality. Users can input project parameters and an Excel file (as shown in Figure 3), upload to the tool, then double check before running the tool, as shown in Section (a). Section (b) displays a sample Area of Review (AoR) result and final pressure counter map with the optimized well pattern, while Section (d) presents a sensitivity analysis tornado chart considering 14 variables. Both Section (b) and (d) correspond to the module ‘Max Storage Capacity’, suitable when the project is at early stage, and the reservoir geometry and well injectivity are to be determined. Section (c) is the output of another module ‘User given inputs’, showcases the final pressure distribution along with AoR by providing a user-input well pattern and reservoir geometry. Section (e) provides a GIS illustration of that well locations and AoR. The tool also conducts sensitivity analyses to understand the impact of uncertainties in input parameters on model predictions, supporting risk assessment and decision-making. A key advantage of EASiTool is its rapid provision of scientifically grounded estimates for storage capacity and reservoir pressure evaluations. Users can obtain reservoir-scale storage capacity estimates within minutes or even seconds. Moreover, the improved web-app environment provides a better UI/UX experience, and users can interact with the tool, changing certain parameters and rerun the tool conveniently, and downloading either the output figures or output data by just clicking the download button.

2. Case study:

To avoid conflict of interest, a synthetic case, Field X CCS project (by using the rock property of Wilcox formation, and a random location in the Austin area) is studied here. The project data and reservoir/wells parameters are listed below, and the input file is at https://gccc.beg.utexas.edu/easitool/app/.

Table 1 Field X CCS project well parameters.

Well Number	Well Location X (UTM)	Well Location Y (UTM)	Injection Rate (MMT/yr) **OR** Extraction Rate (bbl/day)	Max Injection Pressure (psi) **OR** Min Extraction Pressure (psi)
Inj1	616772.6592	3364357.549	0.7	4720
Inj2	617073.6592	3361455.549	0.5	4720
Inj3	626865.6592	3365365.549	1	4720
Inj4	624965.6592	3365745.549	0.2	4720
Inj5	631865.6592	3360845.549	0.5	4720
Inj6	633865.6592	3361745.549	0.3	4720
Ext1	624773.2673	3362558.503	2000	2755.715935

Table 1 lists 6 injection wells and an extraction well in the project. This Field X CCS project is located in the Austin area, and the UTM zone is 14. Through EASiTool calculation, the NPV and total storage capacity of this constant-rate project are reported as 191.66 $M and 9.18 metric million tons (MMT) of CO_2 respectively, making it a profitable project.

The provided output figures and downloadable data files offer a comprehensive insight into the functionality. Figure 3 showcases the parameters and user interface of the input spreadsheet. Users need to provide average reservoir properties, relative permeability coefficients, and project economic properties to evaluate the project's economic performance. In Figure 4, subfigure (a) displays a Pressure Contour Map at the end of injection of this 6 injection wells and 1 extraction well project. The red contour line delineates the AoR and marks the critical pressure increase greater than 350 psi area as the AoR. Subfigure (b) illustrates the extension of the CO2 plume, with black polygons indicating three lease areas hydraulically connected to other parts of the reservoir, and the blue line marking the reservoir boundary. Figure 6 shows the sensitivity analysis outputs by inputting in the Sensitivity tab in the input file (Figure 5). Subfigure (a) depicts AoR prediction with associated probabilities, providing insights into the robustness of the model predictions. Subfigure (b) features a Sensitivity Tornado Chart, offering a visual representation of the impact of various factors on the model's predictions. Subfigure (c) presents a Monte Carlo Simulation for the average Bottom Hole Pressure (BHP) prediction at the end of injection, providing estimated values at P10, P50, and P90 percentiles. If the Maximum Storage Capacity module is selected, total storage capacity percentiles and tornado chart will be shown instead.

Figure 7 integrates a Geographic Information System (GIS) map, highlighting wells, potential AoRs, reservoirs, and lease areas. Together, these figures offer a package of outputs during early site-selection and site-filtering stage, making EASiTool a valuable tool for the evaluation and optimization of geological CO2 storage projects.

Project Name	Field X CCS Project		
Select a simulation module	User Given Inputs		
Reservoir Properties	**Value**	**Range**	**Field Unit**
Initial Pressure	2900.75	>=1015, <=7977	psi
Temperature	149.00	>=122,<=500	F
Thickness	328.08	<=331	ft
Salinity	116545.31	<=233090	mg/L
Porosity	0.20	>0,<=1	-
Permeability	100.00	<=10000	mD
Rock Compressibility	0.00	<=6.895	1/psi
Project Area	38.61	N/A	mile^2
Reservoir Area	115.83	>=Project Area	mile^2
Injection Well Radius	0.33	>=0.164, <=1.64	ft
Injection Duration	10.00	<=100	year
Critical Pressure Increase (AOR calculation)	350.00	<=7252	psi
Relative Permeability Properties	**Value**	**Range**	**Field Unit**
Water Corey Exponent (m)	3.00	>=1, <=6	-
Gas Corey Exponent (n)	3.00	>=1, <=6	-
Endpoint Water Relative Permeability (kra0)	1.00	>=0.1, <=1	-
Endpoint Gas Relative Permeability (krg0)	0.30	>=0.1, <=1	-
Residual Water Saturation (Sar)	0.50	>=0.05, <=0.9	-
Critical Gas Saturation (Sgc)	0.10	>=0.05, <=0.9	-
NPV Properties	**Value**	**Range**	**Field Unit**
Initial Investment	200.00	N/A	$M
Annual Operational Cost (Upstream)	10.00	N/A	$M
Annual Operational Cost (Downstream)	1.00	N/A	$M/well
Tax Credit	85.00	N/A	$/ton
Discount Rate	0.09	0-1	-

Figure 3 Case study parameters and input spreadsheet user interface. The input spreadsheet file and other input data are available at https://gccc.beg.utexas.edu/easitool/app/

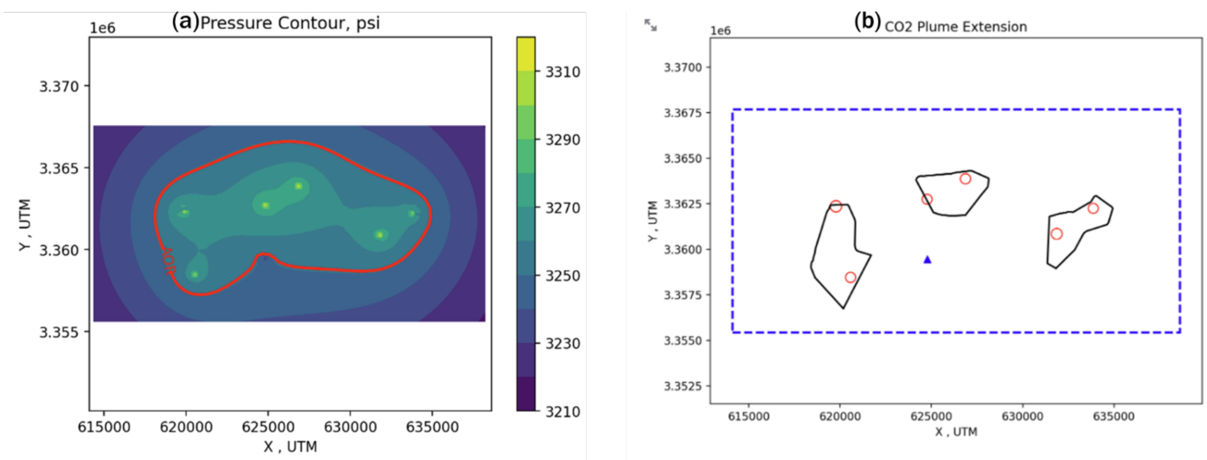

Figure 4 EASiTool figure outputs: (a) Pressure contour map at the end of injection. The red contour line marks the AoR. (b) CO_2 plume extension. Black polygons are three lease areas in this project, which are hydraulically connected to the other part of the reservoir. The Blue line marks the reservoir boundary.

Project Name	Field X CCS Project				
Select a simulation module	Maximum Storage Capacity				
Reservoir Properties	**Value**	**Min**	**Max**	**Unit**	**Range**
Initial Pressure	3147.30	3084.35	3210.25	psi	>=1015, <=7977
Temperature	156.20	153.08	159.32	F	>=122,<=500
Thickness	328.08	321.52	331.00	ft	<=331
Salinity	116545.00	114214.10	118875.90	mg/L	<=233090
Porosity	0.15	0.15	0.15	-	>0,<=1
Permeability	10.00	9.80	10.20	mD	<=10000
Rock Compressibility	3.45E-07	3.38E-07	3.52E-07	1/psi	<=6.895
Max Allowable Injection Pressure	4315.00	4228.70	4401.30	psi	>=Initial Pressure, <=2.0x initial pressure
Relative Permeability Properties	**Value**	**Min**	**Max**	**Unit**	**Range**
Water Corey Exponent (m)	3.00	2.00	4.00	-	>=1, <=6
Gas Corey Exponent (n)	3.00	2.00	4.00	-	>=1, <=6
Endpoint Water Relative Permeability (kra0)	1.00	0.95	1.00	-	>=0.1, <=1
Endpoint Gas Relative Permeability (krg0)	0.80	0.60	1.00	-	>=0.1, <=1
Residual Water Saturation (Sar)	0.20	0.10	0.30	-	>=0.05, <=0.9
Critical Gas Saturation (Sgc)	0.10	0.08	0.12	-	>=0.05, <=0.9

Figure 5 Sensitivity analysis tab. Users can set the min and maximum values of these project parameters. Available at https://gccc.beg.utexas.edu/easitool/app/

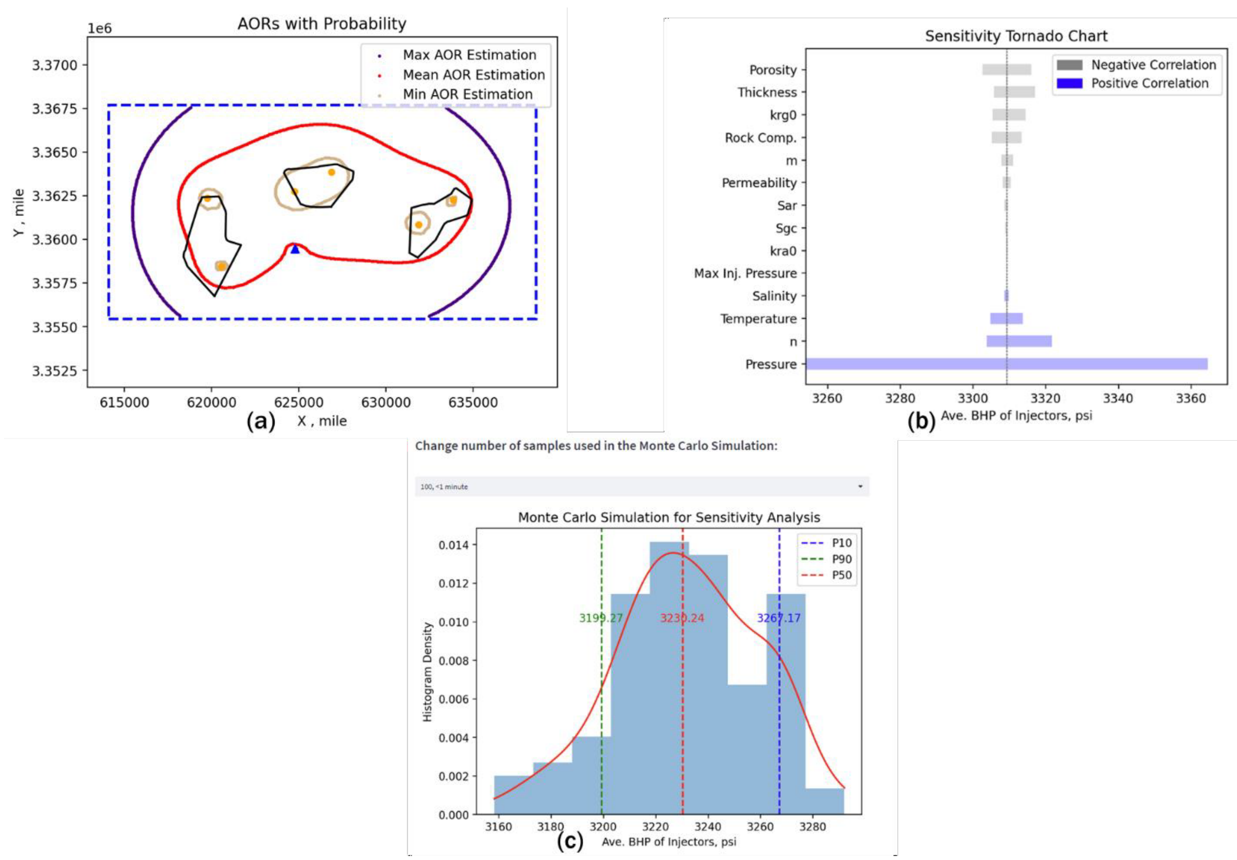

Figure 6 Sensitivity Analysis outputs: (a) AoR prediction with probability (b) Sensitivity tornado chart. (c) Monte Carlo Simulation for average BHP prediction at the end of injection. P10, P50, and P90 values are estimated.

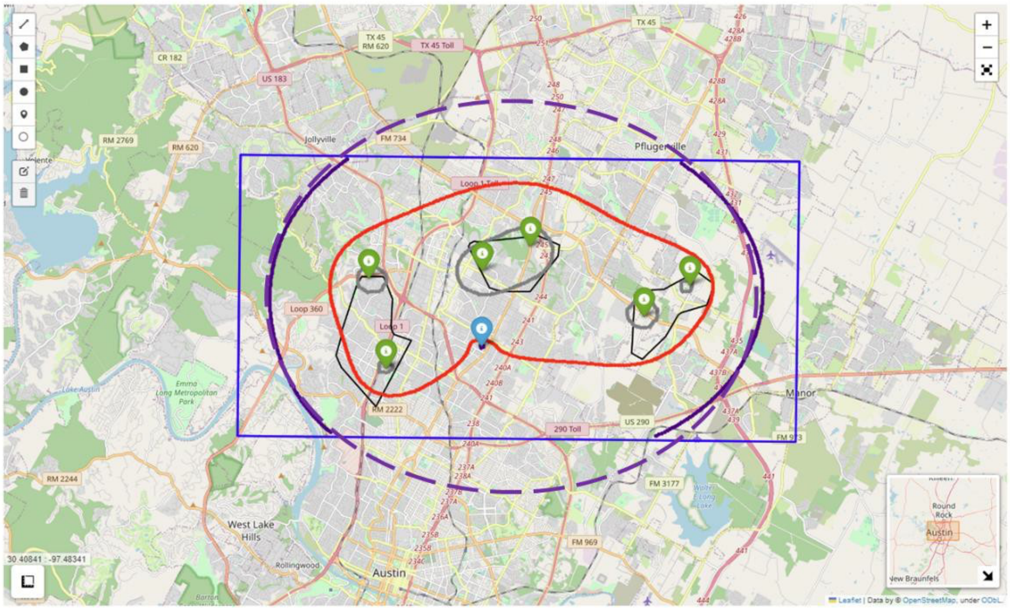

Figure 7 GIS map with wells, potential AoRs, reservoir, and lease areas marked.

Discussion

Recognizing that EASiTool operates as an analytical model, it currently faces challenges in handling intricate reservoir conditions, such as its simplified reservoir model aimed at reducing computational complexity and overlooking certain geological intricacies like geomechanics and reservoir fractures. This tool is still evolving, with efforts focused on incorporating capabilities to address complex pressure boundary conditions and reservoirs containing faults. The forthcoming iterations of EASiTool aim to provide a more comprehensive solution by refining its analytical framework to accommodate a broader range of reservoir complexities. As the development progresses, a more versatile but 'EASi'-to-use tool can be expected which aligns with the intricacies of real-world geological scenarios and EPA regulations.

Conclusions

The new version EASiTool V5.0 is introduced, as a unique tool for CO2 geological storage projects. Its goal is to provide a swift and accurate overall estimation of the storage capacity, site-selection, sensitivity analysis, and economical evaluation & optimization before the project kickstart. It features the following aspects: 1) Application of the advanced closed-form analytical solutions to estimate CO2 injectivity into geological formations; 2) optimization of the number of injection/extraction wells necessary to reach the storage goal; 3) improving Area of Review evaluations by providing predictions with sensitivity analysis; 4) providing initial essential data to apply for Class VI permits. The Field X CCS project is also provided here as a case study to demonstrate the tool's functionality to overall evaluate the CCS project.

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