7-29-2016

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Erin Carlock

Eric W. Peterson
Illinois State University, ewpeter@ilstu.edu

David H. Malone
Illinois State University, dhmalon@ilstu.edu

Recommended Citation

Carlock, E., Peterson, E. and Malone, D. (2016) Three-Dimensional Geologic Modeling and Groundwater Flow Modeling above a CO2 Sequestration Test Site. Open Journal of Modern Hydrology, 6, 182-193. doi: 10.4236/ojmh.2016.63015.

Open Journal of Modern Hydrology, 2016, 6, 182-193
Published Online July 2016 in SciRes. http://www.scirp.org/journal/ojmh
http://dx.doi.org/10.4236/ojmh.2016.63015

Three-Dimensional Geologic Modeling and Groundwater Flow Modeling above a CO_2 Sequestration Test Site

Erin Carlock, Eric W. Peterson*, David H. Malone

Department Geography-Geology, Illinois State University, Normal, IL, USA
Email: *ewpeter@ilstu.edu

Received 1 June 2016; accepted 26 July 2016; published 29 July 2016

Abstract

As temperatures rise and climate change becomes an increasingly important issue, geologic carbon dioxide (CO_2) sequestration is a viable solution for reducing greenhouse gas emissions. Subsurface 3-D modeling and groundwater flow modeling were completed as a component of a CO_2 sequestration feasibility study in the city of Decatur, Illinois. The Decatur Archer Daniels Midland Company Ethanol Plant (ADM) serves as the injection site for a CO_2 sequestration project within a deep saline reservoir. Petrel was successfully used to model the glacial deposits in the area. The 3-D geologic model shows the Peoria Silt, Wedron Formation, and Cahokia Formation at the surface with the Wedron Formation holding up the steep slopes along the east and west banks of Lake Decatur. The groundwater flow model outlined the location of a local groundwater divide and showed flow from the injection site would flow towards Lake Decatur, reaching the lake in 80 days.

Keywords

Carbon Sequestration, Petrel, Hydrogeology, MODFLOW, Glacial Sediments

1. Introduction

Many feasibility and sustainability studies have been conducted to test the concept of carbon dioxide (CO_2) sequestration. The Weyburn Project in Canada [1] [2], the Sleipner Field in the North Sea [3] [4], the deep saline storage partnership among the Midwest Geological Sequestration Consortium (MGSC), Archer Daniels Midland Company (ADM) and Schlumberger Carbon Services in Decatur, Illinois [5] are examples of large-scale se-

*Corresponding author.

How to cite this paper: Carlock, E., Peterson, E.W. and Malone, D.H. (2016) Three-Dimensional Geologic Modeling and Groundwater Flow Modeling above a CO_2 Sequestration Test Site. *Open Journal of Modern Hydrology*, **6**, 182-193.
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questration projects. The Weyburn Project transports CO_2 from the Dakota Gasification Company in North Dakota along a 330 kilometers (km) [206 miles (mi)] pipeline to an oil and gas field in southeast Saskatchewan, Canada [6]. After transfer within pipeline, the CO_2 is injected in an oil field in Canada for enhanced oil recovery purposes and to be sequestered in the subsurface. The Weyburn Project started injecting 5000 tons of CO_2 per day in 2000 resulting in a total of 7-million tons of CO_2 successfully injected and sequestered by 2006 [2].

Another large-scale project is active in the Sleipner Field in the North Sea [3]. Statoil captures CO_2 used in the production of natural gas and injects it 1000 m deep beneath the seabed into a saline reservoir. The project began sequestering CO_2 in 1996 and proved to be viable by 2000, at which point 1 million tons per year were being injected into a reservoir that can hold up to 600 billion tons [7].

The MGSC project is designed to inject 1 million metric tons of anthropogenic CO_2 into a deep saline reservoir housed in the Mt. Simon Sandstone. The project is on the Archer Daniels Midland Company (ADM) property in Decatur, Illinois (**Figure 1**). ADM is an agricultural processing company that produces food-grade ingredients, animal feed, and renewable fuels. The ADM plant is an essential component to this feasibility study because they will be providing not only the land to install the injection well but also the pressurized CO_2 gas that will be injected into the subsurface [8] [9]. With a 500 m thickness, the Mt. Simon Sandstone has storage capacity and a permeability that allows for injection of fluids [5] [10]. Injection began in November 2011, with a total 999,215 tons injected in November 2014.Within the Illinois Basin, Cambrian strata are used to store commercial natural gas, and vertical migration of the natural gas to the surface has been observed. Given the similar geology and physical properties of the fluids, CO_2 leakage is a possibility. Lake Decatur is about 1.60 km east of the injection site and serves as a major water source for the city of Decatur. Therefore, some uncertainty remains as to the dynamics of the injected CO_2 that could pose a risk to water quality in Lake Decatur.

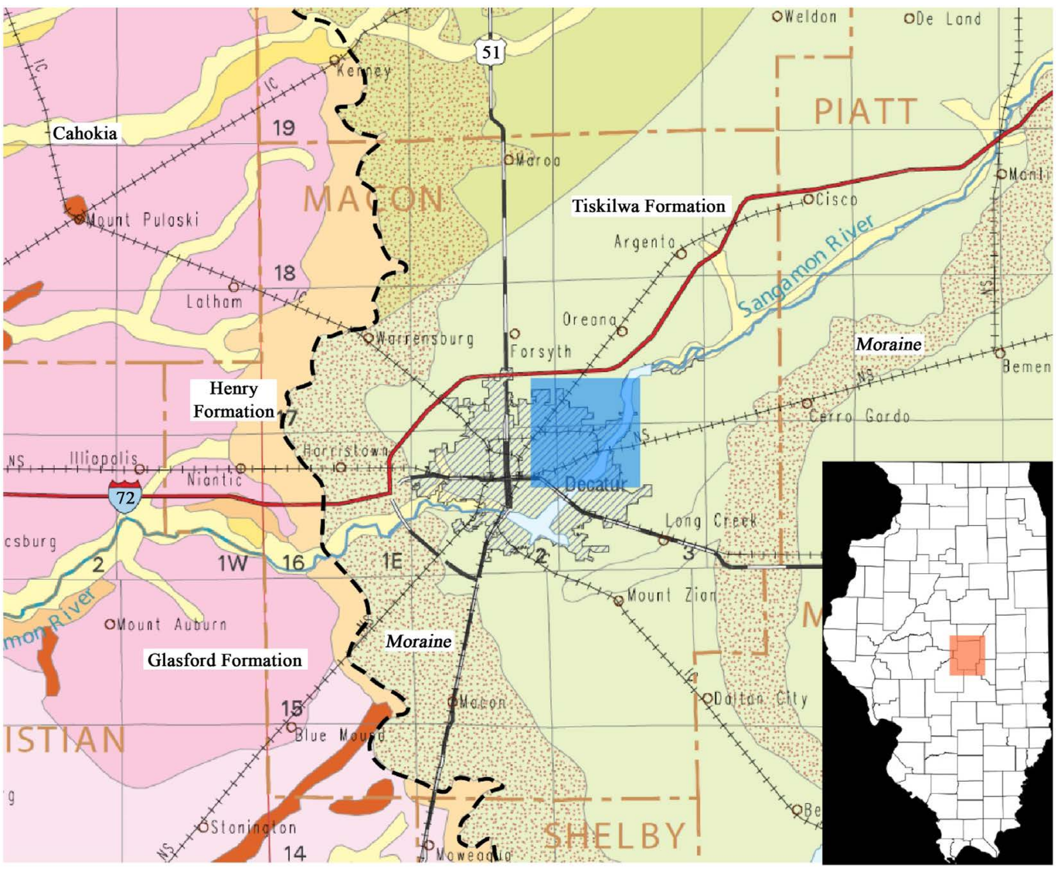


Figure 1. Surficial Geologic Map of the Macon County area, including Decatur (Modified from [11]). Green is Wisconsin till of the Tiskilwa Formation (moraines are indicated by stippling). The pink is various members of the Glasford Formation. Yellow is the Cahokia Formation. Light orange is the Henry Formation. Dark orange is the Illinois Pearl Formation. The dashed line is the Wisconsin terminal moraine.

Potential risks associated with geologic sequestration include leakage, migration, transport of metals or other contaminants in the subsurface, and chemical reactions that may occur in the subsurface [12]-[14]. In the case that the gas migrates vertically, there is the potential for interaction with surface or near surface waters and release into the atmosphere in a hazardous state and concentration.

To better develop this area as a CO_2 sequestration site, information about the near-surface geology and hydrogeology is required. This geologic and hydrogeologic information is crucial to understanding possible migration pathways in the shallow subsurface. With this work, we addressed two main questions: 1) what is the structure and stratigraphy of the shallow geologic units in Decatur area surrounding the ADM site? and 2) what are the characteristics of groundwater flow locally in the Decatur area?

With the advent of sophisticated visualization software, three-dimensional (3D) modeling is becoming a more common tool for understanding subsurface geology (e.g. [15]-[19]. The 3D subsurface modeling was completed to determine the structure and distribution of Quaternary units that overlie the sequestration site and to test the ability of Petrel [20] to model shallow Quaternary (i.e. discontinuous) units. Petrel was developed for bedrock geology modeling, fault modeling, reservoir engineering, geophysical interpretation and stratigraphic analysis making it the industry standard for modeling petroleum reservoirs. This project employs Petrel to model discontinuous Quaternary deposits that overlie the injection site.

In the unlikely event that CO_2 migrates upward, the groundwater flow in the immediate area needs to be understood. Both the Sangamon River, flowing from northeast to southwest, and Lake Decatur serve as the municipal and industrial water sources and lie hydrologically downgradient from the injection site. Therefore, a groundwater flow model was created to investigate the rate and direction of shallow groundwater flow.

2. Methods and Materials

2.1. Geologic Conditions

The Cambrian to Pennsylvanian bedrock strata [21] are overlain by up to 91 m of Quaternary-age glacial deposits. From exploratory drilling, glacial deposits from three separate glaciations were observed (**Figure 2**).

The Cahokia Formation is recent gravel, sand, silt, and clay that is adjacent to the Sangamon River. It is variable in color and is typically less than 5 m thick in the study area.

The Peoria Silt is a wind-blown silt, clay, and fine sand deposit. Within the exploratory holes, the Peoria Silt was seen as a thin 0.5 - 1.0 m surficial layer. It is light olive brown to light yellowish brown in color, laminated, and leached.

The Tiskilwa Formation is a very poorly-sorted deposit composed of very fine silts up to cobbles and boulders [22]. Classified as a diamicton, the Tiskilwa is grayish brown to dark gray in color with a thin, pale yellow oxidized layer at the top. It is calcareous throughout, very stiff, and massive.

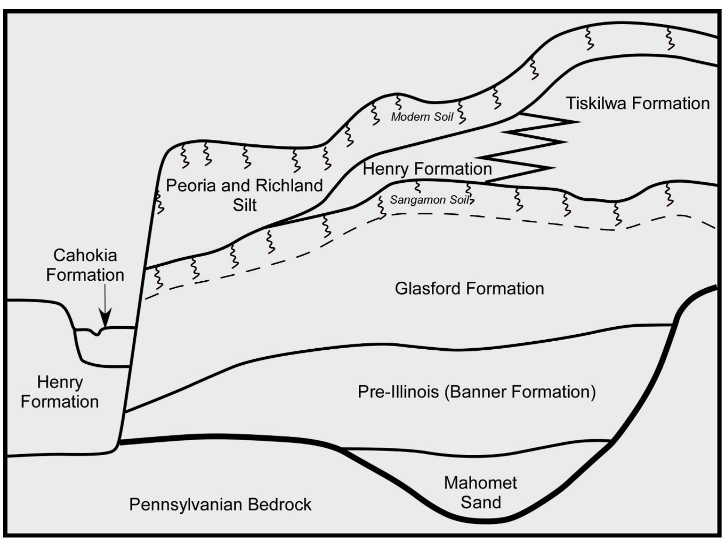


Figure 2. Schematic cross section of the Quaternary units in the study area.

Beneath the Tiskilwa Formation are the Sangamon Geosol, Roby Silt and Glasford Formation, which collectively make up the Illinois glacial deposits seen in the study area [23]. The Sangamon Geosol, an organic-rich, green to gray diamicton, formed on top of Illinois sediments. As an ancient soil horizon, the geosol is oxidized and leached.

The Glasford Formation is a till unit of the Illinois succession. Like the Tiskilwa, it is very poorly sorted, containing very fine silt to cobbles and boulders [24]. Reddish gray in color, the Glasford Formation is calcareous with some beds of poorly sorted sand and gravel.

Pre-Illinois units occur below the Glasford. The Banner Formation is the till member of the Pre-Illinois succession. Present only in the subsurface, the Banner Formation is described in core data as a diamicton loam unit that was dark grayish brown in color, calcareous and very hard.

2.2. Data Sources

Several different types of well data were incorporated into the project (**Figure 3**). Water well data for Macon County were acquired from the Illinois State Geological Survey (ISGS) ILWATER database [25]. Some water well data are only available in paper form, having never been digitized. These data were retrieved from files at the ISGS records office. Coal boring data were obtained from a website hosting all of the coal wells in Macon County maintained by the ISGS [26]. The Geological Records Union at the ISGS provided all original paper copies of oil and gas wells and coal wells in Macon County that were not in the online databases. Lastly, the ISGS drilled eight (8) exploratory holes in the study area as part of the MGSC project [5]; the core data were incorporated into the project.

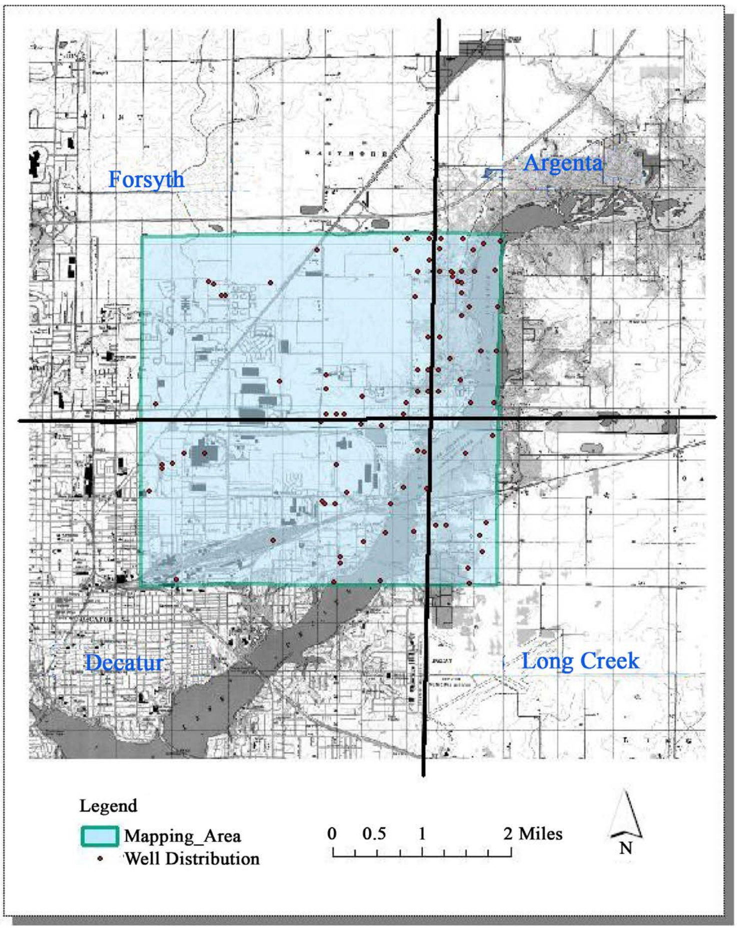


Figure 3. Petrel 3D model domain area indicated in blue. Water well and exploratory boring areas are indicated by red dots. The black lines delineate the four 7.5 minute quadrangles in the area.

2.3. Geologic Model

For the Petrel 3D model, the well data needed to be sorted by township, range, and section to identify the wells within the modeling area. Additional filtering removed wells with logs that were not descriptive, did not provide accurate locations, or were not translatable to geologic units. The data for the useable wells were then put into a spreadsheet. As the Sangamon Geosol is the marker bed between the Wisconsin and Illinois glacial episodes, the presence of the geosol served as a lithostratigraphic "picks" on the well logs. The well logs were first sorted into five sections (**Table 1**). Anything above the Sangamon Geosol was called "Wisconsin" for the Wisconsin Episode glacial deposits, anything representing the Sangamon Geosol was called "Sangamon", anything below the Sangamon Geosol and above any second soil horizon was called "Illinois" for the Illinois Episode deposits, any well that hit bedrock and had any indication of a second ancient soil horizon was called "Pre-Illinois" for the Pre-Illinois Episode deposits. From wells that hit bedrock, the shale or limestone, a classification of "Bedrock" was used. Upon review, the "Wisconsin" was subdivided into two additional layers: The "Cahokia" and the "Peoria". Additionally, the "Sangamon" was combined with the "Illinois", and the "Pre-Illinois" and "Bedrock" were combined.

The next step was identifying the surface elevations for all of the wells. Using ESRI's ArcGIS, a Digital Elevation Map (DEM) acquired from the ISGS Geospatial Data Clearinghouse, four quadrangle maps, and a layer created with the well locations were incorporated into a GIS database. The well layer was created by making a spreadsheet of all of the wells that were be used for the model. API and X, Y data (in UTM format) were included for each well. A surface elevation for each well was determined and incorporated into the well database.

The well data were sorted into separate spreadsheets such that each of the five lithostratigraphic sections had their own spreadsheet. These sections only included the top of each lithostratigraphic unit from each well to create well top data. These well top spreadsheets included the API, X, Y locations, elevation, and lithology.

Using Petrel, a new project was created with five sets of "well tops" folders. Each layer (Cahokia, Peoria, Wisconsin, Illinois, and Bedrock) was imported into their corresponding well top folder, which in Petrel are represented as a series of dots that make up the well layers (**Figure 4**). Each unit was created as a separate layer to ease subsequent editing/adjustment. Next, surfaces were created out of the well top data to generate the model (**Figure 5**) for the Cahokia, Peoria, Wisconsin, Illinois, and Bedrock (**Table 1**).

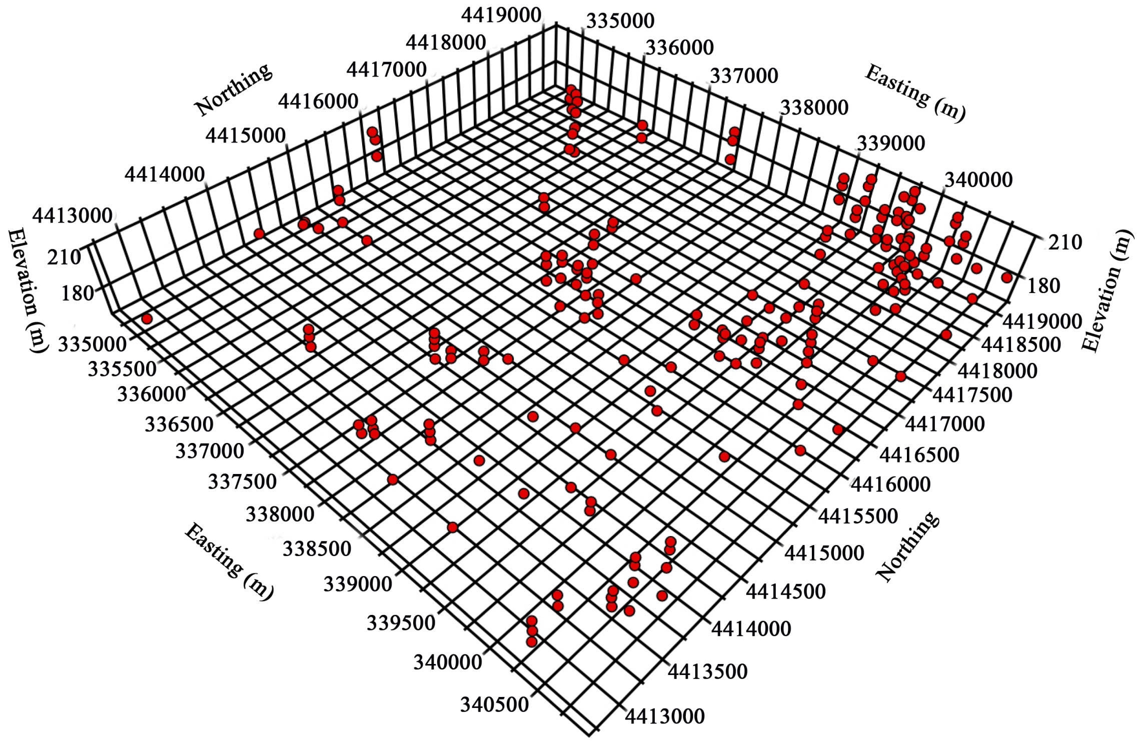


Figure 4. Petrel well top data for initial 3D model.

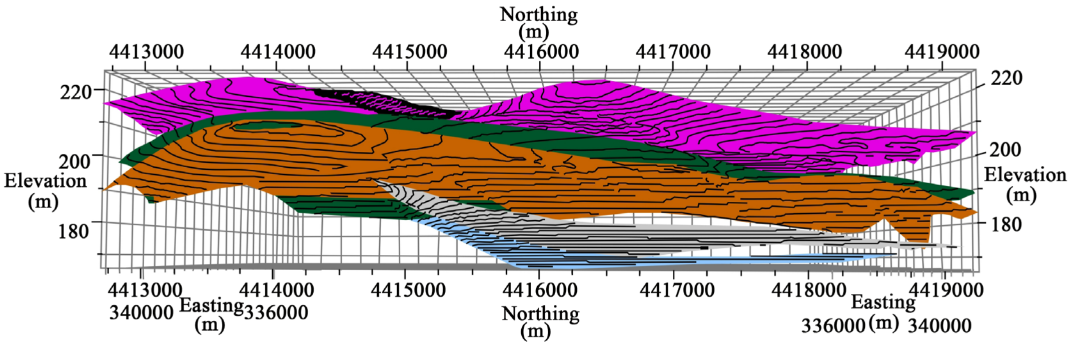


Figure 5. Geologic horizons interpreted by Petrel for initial model from well top data.

Table 1. Key to geology and axes for all Petrel screenshots.

Key	
X-Axis	UTM Zone 16 horizontal grid value.
Y-Axis	UTM Zone 16 vertical grid value.
Z-Axis	Elevation above MSL in feet.
Vertical Exaggeration	5
Cahokia Alluvium	Yellow
Peoria Silt	Purple
Wisconsin Till	Green
Illinois Till	Orange
Bedrock	Blue

2.4. Groundwater Flow Model

To establish and confirm hydrogeologic boundary conditions for the local (shallow) groundwater flow model, GFLOW [27], an analytical element method was used to simulate regional flow through the surficial deposits comprised of diamicton tills and sand and gravel layers that total 15 m in thickness. On the regional scale the hydraulic conductivity (K) was assumed to be homogeneous and isotropic. The Sangamon River, to the east, Spring Creek, to the west, and Lake Decatur, along the east and southeast edge of the domain were near-field elements represented as constant head (Dirichlet) conditions. Model parameters were measured on site, calibrated by the model, or estimated using data acquired from the ISGS exploratory holes (**Table 2**). An initial simulation was conducted with GFLOW to establish regional flow and to aid in the development of local flow conditions (**Figure 6**).

The local groundwater flow model was developed using MODFLOW [28]. Using a uniform 0.15 km x 0.15 km cell (0.23 km^2), a 40 row × 40 column grid represented the domain (**Figure 7**). Aquifer parameters and conditions used in the GFLOW model, with the exception of K, were used for the MODFLOW development. Rather than the 12 m/day, the local model calibrated to a K value of 0.12 m/day. The boundary conditions for the model domain were represented as constant heads, with values established from the GFLOW simulation (**Figure 6**). Spring Creek, Sangamon River, and Lake Decatur were also incorporated into the domain as constant head cells. Head values for Lake Decatur were obtained from a gauging station about 2 km downstream of the study area. (Haring, Pers. Com.). Recharge for the simulation was set at 10% (0.101 m/yr) of the average annual precipitation rate for Decatur, Illinois of 1.01 m/yr [29]. The use of 10% is consistent with other groundwater flow simulations in central Illinois.

Particle tracking, using MODPATH [30], was used to further delineate the location of a groundwater divide identified with the GFLOW simulation (**Figure 6**). The horizontal migration was simulated by centering particles on the injection site and forward modeling. The time for the first particle to reach Lake Decatur signified the travel time.

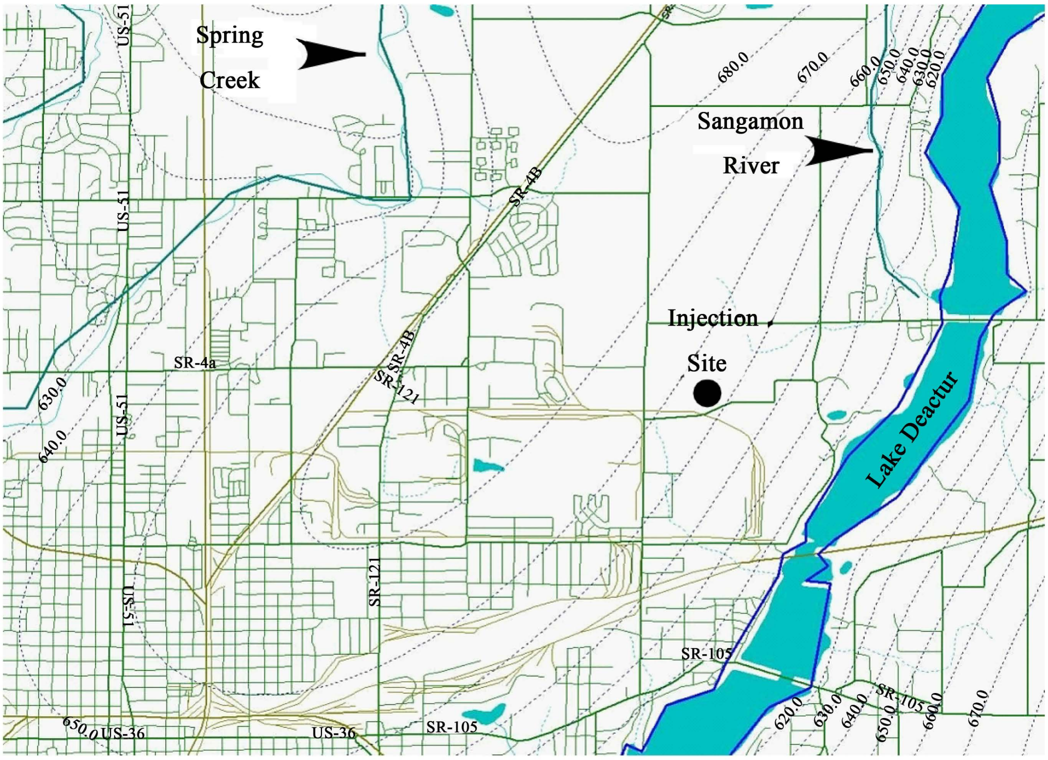


Figure 6. GFLOW model of the area with flow lines in gray. Also shows Lake Decatur and the sequestration injection site.

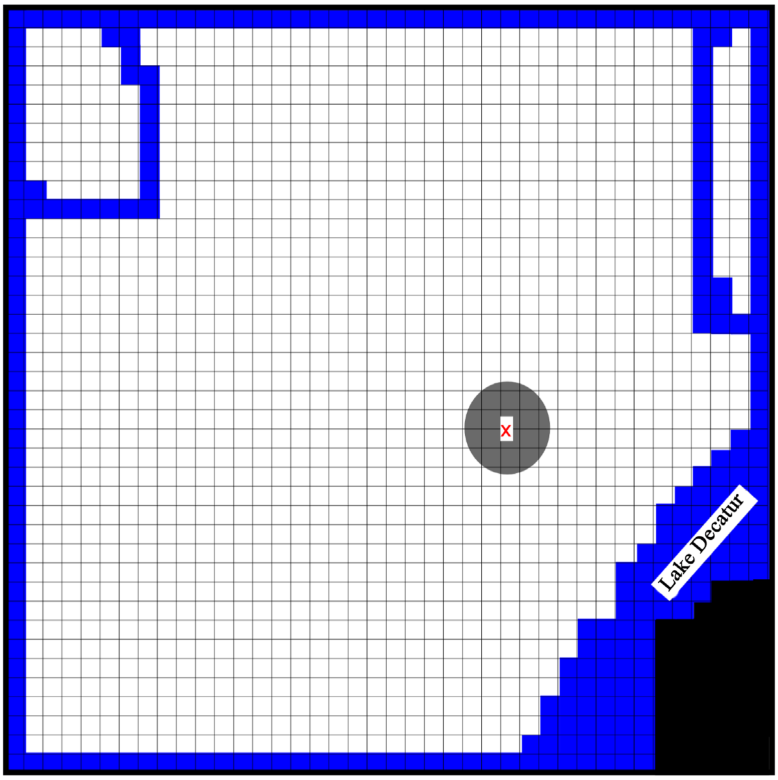


Figure 7. The 40 × 40 MODLFOW grid over study area with boundary conditions included. Blue cells represent constant head conditions. Black cells are inactive cells. Gray circle represents the location of the sequestration site.

Table 2. Parameters used for GFLOW model.

Aquifer parameters	Value	Source
Base elevation	134 m	Field data
Thickness	15 m	Field data
Porosity	0.2	Estimate
Hydraulic conductivity	12 m/day	Model calibration
Recharge	0.24 m/year	Model calibration

3. Results

3.1. Geologic Model

The Petrel model simulates Quaternary deposits overlying Pennsylvanian bedrock in the Decatur area, indicating glacial sediment thicknesses up to 50 m (**Figure 8** & **Figure 9**). The Peoria Silt thins to the northwest and to the east where the lake is present. The resistive Wisconsin till is responsible for creating higher slopes along the east and west edges of the Lake (**Figure 8**). The Peoria Silt terminates at the top of these slopes along the western boundary of Lake Decatur and picks up along the flat lying areas west of the lake. Waters of the Sangamon River completely eroded the Wisconsin till unit beneath the lake and exposed the lower Illinois till. Fluvial processes associated with the Sangamon River have deposited a thin layer of Cahokia Alluvium within the floodplain and along the bottom of Lake Decatur where the Peoria silt and Wisconsin till units had previously been deposited.

The surface layer of the geologic model (**Figure 6**) includes the Cahokia alluvium, which is present in the streambed, the Peoria Silt, representing about 85% of the surface deposits, the Wisconsin till, occurring along the lake edges and in the northwest and east corners of the modeling area, and the Illinois till, which is present below the thin Cahokia alluvium in the lake bed. The Petrel model of the surficial geology is consistent with the published surficial geology map of the area [31].

3.2. Groundwater Flow Model

The local groundwater flow model identified a NE-SW trending groundwater divide in the northwestern portion of the domain (**Figure 10**). Flow on the northern side of the divide is to the northwest, and flow along the southern side of the divide is to the southeast. The model simulated groundwater flow at the injection site would move to the southeast towards Lake Decatur. The forward modeling with MODPATH indicated that the particles placed at the injection site reached Lake Decatur in 80 days.

4. Discussion

While Petrel is used mainly for subsurface modeling of continuous stratigraphic units in the petroleum and gas industry, this project indicates that Petrel has the capability to model discontinuous Quaternary units. To address the problem of modeling discontinuous units, a stratigraphic column consistent across all wells is needed; thus, an absent unit in a well is assigned a thickness of zero (0) meters. Where this occurs, the model result is a pinch out of the unit, excluding it accordingly. The modeling process in Petrel also required simplification (*i.e.* upscaling) of the Quaternary units because they are heterogeneous, with discontinuous lenses of sediments of various size, *i.e.* sand and gravel lenses. While Petrel is capable of distinguishing facies within units given high resolution log data [17] [19], the discontinuous nature of the lenses may be too detailed to model accurately. We did not address this issue. Rather, we modeled the materials on a unit/formation level (low resolution), homogenizing the units, instead of at the facies level. This simplified the model and produced fewer layers. The standard input procedures were also altered in order to model the Quaternary units. An additional method deviation was importing surfaces of well top data separately rather than collectively. This method allowed alterations of surfaces to be more efficient; if a surface needed to be altered, which it did frequently, only one layer was modified rather than the entire model.

A concern for broader project is that there are thick sand and gravel bodies within the glacial deposits or frac-

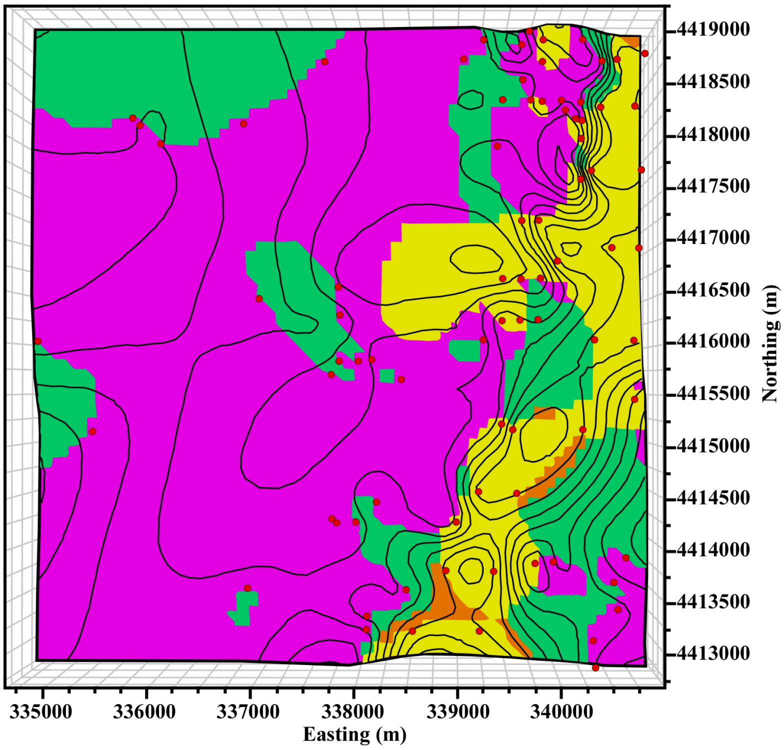
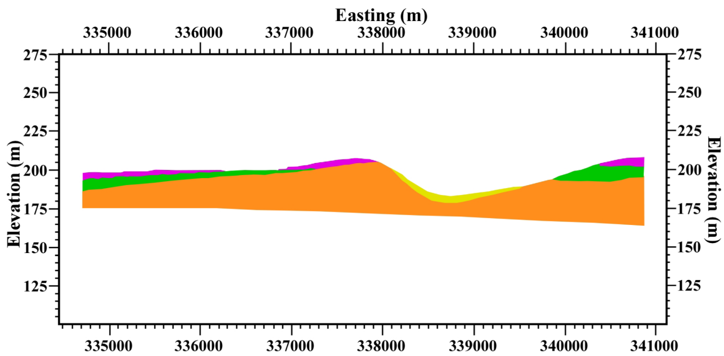
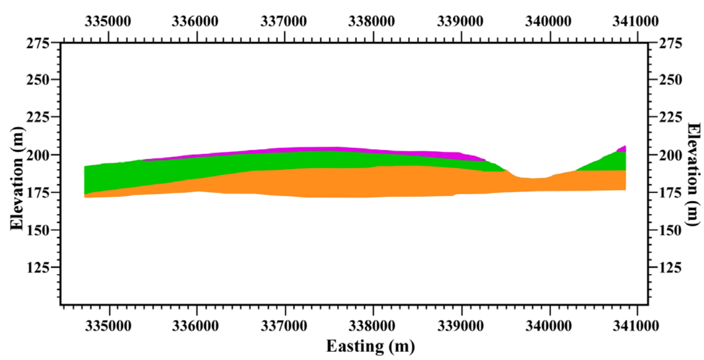


Figure 8. Plan view of the final Petrel model illustrating the surficial geology. The black circle is the estimated extent of the gas plume once it is injected and red dots show well distribution. Contour interval is 5 meters.



(a)



(b)

Figure 9. Petrel generated (a) east-west cross section along the southern margin of the geologic model (4412800 line); (b) east-west cross section along the 4415200 line of the geologic model.

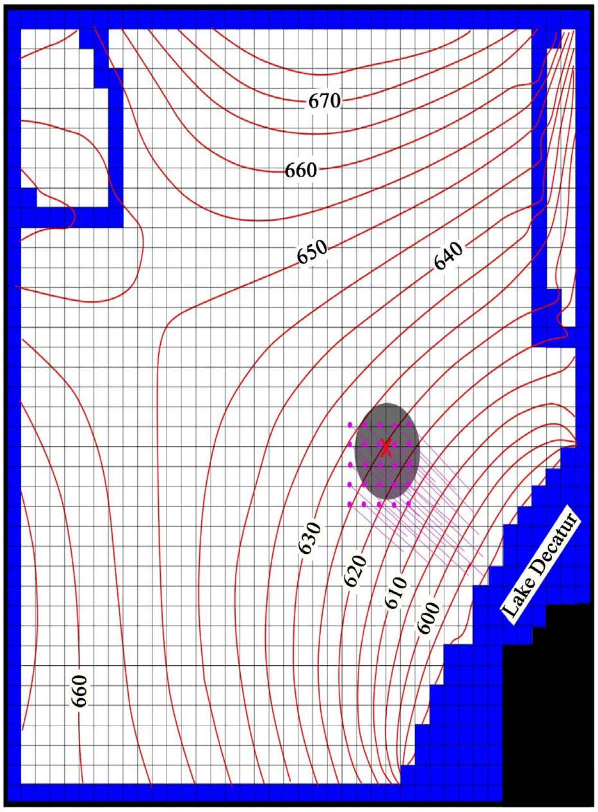


Figure 10. Average head values are in red (contoured in feet). Projected gas plume at depth is the gray circle. The red X marks the position of the injection well. Results of the average flow MODPATH simulation with particles and flow paths in purple. This represents the position of the particles after 80 days.

tures in the bedrock surface that may act as significant migration pathways for gas if there is a shallow leak or if gas migrates vertically from deeper in the bedrock units. It is assumed that the overlying till can act as a cap layer given the combined thickness of the glacial units and the overall composition as being fine-grained, poorly sorted and believed to possess a low permeability and porosity. However, the unweathered till can have significant vertical and horizontal fracture permeability that will allow migration [32]. Additionally, all glacial till units have extensive lenses of sand and gravel that can act as lateral and/or vertical migration pathways.

Fluid flow in the shallow subsurface will be transported towards Lake Decatur. Any vertical leakage from the deep saline reservoir would take years, if not 100s of years, based upon vertical fluid migration from an oil and gas field [33]. Additionally, the successful injection of nearly 1,000,000 tons of CO_2 [6] reveals the feasibility of the reservoir. However, once in the glacial sediment, migration to the lake would be on the order of 10s to 100s of days. Since glacial units vary in composition such as the presence of discontinuous sand and gravel lenses, flow rates through the units will vary as compared to the model. However, the general direction of groundwater flow will remain the same, towards Lake Decatur.

5. Conclusions

Petrel is used traditionally for subsurface modeling of deep, continuous bedrock systems by the petroleum and gas industry. This project successfully tested the program's ability to model discontinuous Quaternary units. To combat this problem of modeling discontinuous units, a consistent stratigraphic column across all wells was used to so where a unit was absent in a well, it was included with a thickness of 0'. Using this method, a successful geologic model was created with stratigraphic units pinching out as needed honoring the well data. The Quaternary units also had to be simplified in order for the Petrel modeling process to work. Since there are mostly till deposits above bedrock in this area with a thin layer of loess on the surface, modeling was from a somewhat low resolution. Any sand deposit encountered in a well log less than 0.67 m thick was combined with the surrounding material. This simplified the facies within the major till units resulting in a simplified model with fewer layers. The standard Petrel model input procedures were also altered in order to map the Quaternary units. Well top data were imported as separate stratigraphic surfaces rather than being associated with individual wells resulting in the seamless ability to alter or edit surfaces as needed. Overall it can be concluded that Petrel has the ability to model discontinuous geologic units.

The resulting model is an accurate representation of Quaternary deposits in the Decatur area. They are up to 48 m thick in some places and thinner or eroded completely where Lake Decatur has cut through. The Peoria Silt covers most of the surface except on the topographic high slopes along the edges of Lake Decatur. In these places, the Wisconsin till is present along with the flat, higher areas in the northwest corner of the mapping area. The Cahokia alluvium fills in the streambed of Lake Decatur where it has completely eroded the Peoria Silt and Wisconsin till deposits. The geometry of the Quaternary units in this area is somewhat simple, though the composition is mostly consistent.

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