TOPICAL REPORT: ROCKY MOUNTAIN REGIONAL CO_2 STORAGE CAPACITY AND SIGNIFICANCE

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Abstract

The purpose of this study includes extensive characterization of the most promising geologic CO_2 storage formations on the Colorado Plateau, including estimates of maximum possible storage capacity. The primary targets of characterization and capacity analysis include the Cretaceous Dakota Formation, the Jurassic Entrada Formation and the Permian Weber Formation and their equivalents in the Colorado Plateau region. The total CO_2 capacity estimates for the deep saline formations of the Colorado Plateau region range between 9.8 metric GT and 143 metric GT, depending on assumed storage efficiency, formations included, and other factors.

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Executive summary

This document reports developed procedures and results of regional CO_2 storage capacity estimates for deep saline formations on the Colorado Plateau. Determining storage capacity estimates was one of the major tasks of this project. The Cretaceous Dakota Formation, the Jurassic Entrada Formation and the Permian Weber Formation, mainly occurring in the northern sedimentary basins of the Colorado Plateau Region were the main emphasis of this study. In the southern part of the region, the Cedar Mesa, De Chelly, and Hermosa Formations, stratigraphic equivalents of the previous mentioned Formations, and the Leadville Formation were evaluated.

The Geological Surveys of the four states in which the Colorado Plateau Region is located, AZ, CO, NM and UT, were asked to improve the regional geologic assessment of the listed formations. For three out of the four states that was accomplished by generating structure and thickness contour maps for each of the formations they were responsible for. These maps were not just based on interpolating well-derived data but also incorporated additional available data. In addition, each of the partnering geologists contributed in depth sedimentary basin expertise during the compilation of the regional geology. Besides digital contour maps, the surveys also provided regional porosity data and geothermal gradient values.

The project team developed a five-step workflow method, combining GIS procedures and spreadsheet calculations to convert the input data generated by the Surveys into the by NETL predefined Atlas format. This first step consisted of extracting depth and thickness values from the contour maps by converting the data to 1–km^2 gridded data using GIS tools. After the grid attribute values were converted to point data, they were further manipulated to calculate CO_2 density values based on temperature and pressure data derived from the depth values. The CO_2 capacity values, at the three different efficiency factors, (0.51%, 2% and 5.4%) were derived by integrating the CO_2 mass and the available pore volume derived from thickness, grid cell area and porosity. These capacity estimates were further manipulated in GIS to resolve data problems that occurred along State Boundaries and to integrate the points for each formation into a single feature class across State Boundaries. Finally the data were aggregated into 10km^2 predefined polygons and all data were integrated into a single GIS geodatabase.

The total CO_2 capacity estimates for the deep saline formation of the Colorado Plateau Region range between 13.5 metric GT and 143 metric GT depending on the applied efficiency factor. These values are reduced to 9.82 metric GT and 103.96 metric GT when only the three main saline formations are taken into consideration. The CO_2 storage capacity estimates resulting from this study represent an approximate 8% decrease when compared to the capacity numbers reported for the previous atlas version. These estimates can account for up to 120 years of regional CO_2 storage.

List of Abbreviations

AGS	Arizona Geological Survey
ARRA	American Recovery and Reconstruction Act
AZ	Arizona
CCS	Carbon Capture and Storage
CGS	Colorado Geological Survey
CO	Colorado
CO_2	Carbon dioxide
CSV	Comma Separated Values (text file)
DEM	Digital Elevation Model
DOE	Department of Energy
EGI	Energy and Geosciences Institute
ESRI	Environmental Systems Research Institute
gdb	Geodatabase
GHG	Green House Gas
GIS	Geographic Information System
GT	Gigatonnes (= 1 billion Tonnes)
mpk	Map package
NATCARB	National Carbon Sequestration Database and Geographic Information system
NETL	National Energy Technology Laboratory
NM	New Mexico
NMBGMR	New Mexico Bureau of Geology and Mineral Resources
RCSP	Regional Carbon Sequestration Partnerships
RMCCS	Rocky Mountain Carbon Capture and Storage
shp	Shape file (GIS file)
TDS	Total Dissolved Solids
U.S.	United States
UGS	Utah Geological Survey
USDW	Underground source of Drinking Water
UT	Utah
xls	Excel spreadsheet file

1. Background/Introduction

The 'Characterization of Most Promising Sequestration Formations in the Rocky Mountain Region', project was one of the ten projects selected by the National Energy and Technology Laboratory (NETL) that received Department of Energy (DOE) funding, provided by the 2009 ARRA act, to characterize promising geologic formations for permanent CO_2 storage. Evaluating geologic formations in terms of assessing available CO_2 storage capacity and their associated uncertainty quantification are important factors in the implementation of geologic Carbon Capture and Storage (CCS). Developing and improving CCS technology has the potential to play a major role in reducing Green House Gas (GHG) emissions (Bachu et al. 2007).

This particular project focused on the site characterization of high-potential deep saline storage formations on the Colorado Plateau in the Southwestern US. Deep saline formations are one of the three geologic environments that are suitable to sequester CO_2. The other two are depleted oil and gas reservoirs and un-mineable coal layers. The Regional Carbon Sequestration Projects (RCSP) assess the regional, CO_2 storage capacity whereas this Site Characterization project focused on the Sand Wash Basin in NW Colorado. The project's larger scale allowed for more in depth assessment of not only the target formations but also the seals and the underground sources of drinking water (USDWs). The entire project team was made up of the following partners: NETL-DOE, the University of Utah, the Arizona Geological Survey, the Colorado Geological Survey, the New Mexico Bureau of Geology & Mineral Resources, the Utah Geological Survey, Schlumberger Carbon Services, Tri-State Generation and Transmission Inc., and Shell Oil Company. The project this report is based on started in December of 2009 and ended at the end of September 2013.

The main focus at the Craig, Colorado project site was to study the regionally occurring storage formation candidates: Cretaceous Dakota, Jurassic Entrada and Permian Weber Sandstones. Detailed data were obtained from 131 feet of core recovered from the 9,745 deep single well drilled near the Craig Power station, a coal-fired electric generating station. Less detailed data for the same target formations were compiled across the Uinta, Piceance and Sandwash Basin on the northern Colorado Plateau. Besides the three main target formations, the stratigraphic equivalents of these formations were also studied in the southern part of the Colorado Plateau. The equivalents include the Permian Cedar Mesa and De Chelly Sandstones, and the Pennsylvanian Hermosa Formation in the San Juan, Paradox and Black Mesa Basins. The Mississippian Leadville Formation of the San Juan Basin was included as well.

2. Objectives

This topical report describes the workflow created to process data for 'Characterization of most promising sequestration formation in the Rocky Mountain Region' project. One of the project tasks was to assess the regional significance of these ubiquitous regional formations. The project also required refining existing carbon capacity estimates based on existing data to determine if formations can store 30 million tons of CO_2. The national NATCARB Carbon Sequestration database was updated with the generated regional data. It was therefor necessary to integrate the regional deep saline geology information into a coherent and consistent single dataset across state and sedimentary basin boundaries. These data also have to comply with NETL's NATCARB data structure from which data can be queried to estimate CO_2 storage capacities on a national scale. The Colorado Geological Survey (CGS), the Arizona Geological Survey (AGS), New Mexico Bureau of Geology & Mineral Resources (NMBGMR) and the Utah Geological Survey (UGS) together with the University of Utah contributed to this task in particular.

The University of Utah developed a workflow that could be used or adapted by each of the four State geological surveys. The workflow allowed AGS, CGS, NMBGMR and UGS to transform their regionally compiled data into a format from which data could be integrated across state boundaries. Eventually, the data for all the formations were merged into a single database. The database provides the original data and their derived attributes. The resulting capacity data can be queried at a 1-km^2 scale or can be aggregated into 10 km^2 polygons conforming to NETL's NATCARB saline formation Atlas format. Geologists from the State surveys created the regional data for the saline formations and the University of Utah spearheaded the coordination, the development of a workflow that can be used for future regional data compilations, the data integration across the state boundaries and the aggregation of the data at the 10 km scale. University of Utah then formatted the regional data in accordance with the NATCARB saline-atlas template.

Several steps were required to convert the regional data provided by the geological surveys before calculating the regional CO_2 capacity values. After the surveys compiled the regional data for their state, the University of Utah's role was initially focused on creating a common workflow system that served as a framework. The states were asked to create their original input data in a GIS format from which the required parameters could be extracted at a 1-km^2 spatial resolution. While the states were working on this task, the University developed an excel spreadsheet based on the CO_2 capacity spreadsheet used previously for capacity calculations in the southwestern US. Besides the CO_2-density macro, a new worksheet was generated to prepare the data points for integration into the GIS database. The manipulated GIS data became the input for the NATCARB Carbon Atlas format. The purpose of the spreadsheet is to replace a visual basic script used for previous NATCARB Atlas capacity calculations. It used to run within ArcGIS™ version 9, but did not run properly anymore under version 10. Since ESRI™ is phasing out Visual

Basic scripts in their GIS software and the expertise to modify the script was not available in the project team, it was decided to look for an alternative solution. Mimicking the functionality of the script in an Excel spreadsheet had the advantage that the method is more transparent to the GIS analyst. A drawback of the spreadsheet calculations is a greater potential for operator mistakes.

This study determined that the potential CO_2-storage capacity for the three main regional saline formations ranges between 9.8 and 103.9 billion metric tons depending on the efficiency factor. When compared to the 2012 Atlas IV data the total CO_2 storage capacity of these three formations decreased by approximately 8%. Including the stratigraphic equivalents increased the total CO_2-storage-capacity-estimate to a range between 13.6 and 143.7 billion tonnes depending on the efficiency factor. Since not all the equivalent formations were included in the Atlas IV data, a comparison cannot be made. The relatively simple, volumetrically based, regional-resource estimates did not take geologic complexity, presence or absence of seals, or different trapping mechanisms into account. The numbers also do not take economical or technical constraints into account.

In summary, this report describes the general GIS workflow process applied to transform the data delivered by the four involved State Geological Surveys into the NATCARB Atlas structure. Additionaly, this reports touches on the specific issues stemming from different groups processing their data more or less independently. And, it outlines remaining problems and presents suggestions for how to improve the data and the workflow process.

3. General CO_2-capacity-calculation methodology

3.1 Previous Southwest Region Atlas methods:

The first CO_2 capacity data for the South West Region were created by drawing generalized cross sections through the sedimentary basin to derive average data for thickness and depth of the formations. Average, local geothermal gradients were used to calculate reservoir temperatures. The hydrostatic pressure at the top of the formation was derived by applying the hydrostatic pressure gradient of 1MPa/km (0.433 psi/ft) to the depth of the top of the formation. These values allow calculating the CO_2 density at depth. Average porosity values for the formation were applied to derive the pore volume. Combining the total pore volume with the average CO_2 mass – derived from the CO_2 density – provided the initial CO_2 capacity values. In a later version of the methodology low, medium and high efficiency factors were applied to the total CO_2-storage capacity. These efficiency factors, corresponding to P10, P50 and P90 probability distributions derived from Monte Carlo simulations reflect the fraction of the pore space that will be occupied by the injected CO_2 (U.S. DOE 2012). For the NATCARB Atlas III data, the methodology was modified to include information extracted from well data in the public domain and commercial well databases. Existing well depth and thickness values were interpolated between the wells and extrapolated to the extent of the basin. Where only one data point was readily available, that data point's values were assigned to the entire basin, which creates a lot of uncertainty. For the NATCARB Atlas III southwest region data, the CO_2 density was calculated using an iterative method based on the Modified Redlich-Kwong equation of state and standard thermodynamic equations (Han and McPherson 2008). Previous versions of southwest regional Atlas data used a 3000' (914.4m) depth of the top of formation cut-off to estimate the CO_2 capacities. This is a slight deviation from the NATCARB Atlas protocol, which suggests an 800m minimum depth (U.S. DOE 2010). To maintain consistency within the southwest regional data, to which this project's data eventually will be merged, that cut-off of 3000' was maintained. No thickness or maximum depth data cut-off values were imposed on the CO_2 capacity estimates. For Atlas IV the range of the efficiency factors was tightened from a 0.4 - 5.5 to 0.51 – 5.4. The data from the current ARRA project will be merged with the Atlas V data, the anticipated 2014 version of the NATCARB CO_2 Atlas. At the moment of this writing, no updated NATCARB calculation methodology or database structure has been communicated to the project. The methodology described in the rest of this report reflects an update of how the improved regional saline data prepared by the state surveys was processed in preparation for eventually being merged with the RCSP Atlas V data.

3.2 NATCARB saline formation CO_2 storage resource estimates methodology

Carbon dioxide (CO_2) capacity calculations require several input data parameters. This project used the volumetric calculation method described in the NATCARB Atlas (U.S. DOE 2010) given by the following equation:

$$GCO_2 = A_t h_g \Phi_{tot} \rho E_{saline}$$

This formula generates the **CO_2 storage resource mass estimates** (GCO_2) based on combining data for the total area (A_t), gross formation thickness (h_g), total porosity (Φ_{tot}), CO_2 density (ρ) and the storage efficiency factor (E_{saline}). The first two input parameters account for the total bulk volume; the CO_2 density converts the reservoir volume of CO_2 to mass while the storage-efficiency factor reflects the fraction of the total pore volume that will be occupied by the injected CO_2.

The **total area** represents the extent of the formation 3000' below the topographic surface. To be able to take the variations in the other contributing variables across the extent of the formation into account, the total area was discretized into a centroid-centered grid with 1-km^2 cells using GIS techniques, which will be explained later. An equal area projection was used to assure that the area of the each cell was not distorted and kept equal throughout the project region. The CO_2 storage capacity was calculated for each of the 1-km^2 cells of the formation that is present below 3000'. The formation totals were obtained by summing the data of the contributing cells.

The **gross formation thickness** for each cell was extracted from the 1 km^2 discretized regional isopach maps provided by the four geological surveys of the states participating in the project. The volume of the formation at the center of cell was obtained by multiplying the thickness with its area (1 km^2).

Multiplying the bulk volume by the **porosity**, a parameter provided by the surveys, generated the available pore volume. Generally, an average constant porosity value was applied for the entire formation across the basin except for the Uinta Basin Weber formation, for which location dependent values were derived by spatially interpolating existing well porosity data.

The **CO_2 density** at the top of the formation was calculated based on the modified Redlich-Kwong equation of state using an Excel Visual Basic macro. The algorithm in this macro requires temperature and pressure as variable input parameters depending on the depth. Neither of those 2 variables is readily available from well data but they can be approximated from the depth of the top of the formation. The top of the formation and not the middle of the formation depth was selected as reference point because the super critical CO_2 fluid will rise to the top from the buoyancy effect. The temperature was approximated using the geothermal gradient, whereas the hydrostatic gradient was used for pressure. The geothermal gradient can either be calculated from measured bottom hole temperatures or set to one corresponding to heat flow within the sedimentary basin. The density parameter combined with the pore volume allows for the conversion to CO_2 mass

The **efficiency factors** applied to the CO_2 mass reflect the fraction of the pore space that will be occupied by the injected CO_2. Three different factor magnitudes are used reflecting a low, medium and high estimate: 0.51%, 2% and 5.4%

3.3 Methodology workflow update

The general workflow for converting the regional geologic information provided by the four state geological surveys, to CO_2 capacity numbers compliant with the NATCARB saline Atlas data format consisted of 6 major steps listed in Table 1. ESRI's™ ArcGIS software package was used for the GIS platform and Microsoft Excel™ was used for the spreadsheet calculations.

Table 1: Major methodology workflow steps:

Workflow step	Processing environment	Data Scale	Responsibility
1. Regional Data Preparation	GIS	Regional	AZ, CO, NM & UT Geological Surveys
2. CO_2 storage capacity calculations	Spreadsheet	1 km^2	State Surveys and University of Utah
3. Creation of GIS CO_2 storage capacity point database	GIS	1 km^2	University of Utah
4. Edge matching formation data across state boundaries	GIS & spreadsheet	1 km^2	University of Utah & State Surveys
5. Integration of the regional 1-km-spaced Rocky Mountain CO_2 capacity GIS database	GIS	1 km^2	University of Utah
6. Aggregating (upscaling) the data into 10 km^2 NATCARB predefined polygons	GIS	10 km^2	University of Utah

3.3.1 Regional data preparation:

a. State Geological Survey Regional Data

The partnering State Geological Surveys generated the input parameters required for the CO_2 storage capacity equation applying different methods. This report provides an overview of the parameters and describes the workflow, in general. The set of states' assessments generally resulted in two contoured surfaces for each deep saline formation of interest within a basin (Figure 1). The first was a contoured isopach and the other a 'top of formation' structure surface. The contours were derived from available well information, expert knowledge of the basins and ancillary data where available. By only applying computer interpolation to the well data NM was the exception to this method. The manual contouring process allowed the geologist to include structural basin knowledge that cannot easily be incorporated using mathematical interpolation of well data attributes only. These contour lines were converted to records with a 1km spacing covering the entire area where the formation occurs at depth within the sedimentary basin. Later in the workflow the 1 km^2 point data were aggregated into predefined 10 km^2 NATCARB Atlas cells. Besides the contour lines, the surveys also provided porosity data and geothermal gradients. The four required capacity estimate input values were included in the delivered spreadsheet or in the geodatabase, containing formation records at the 1-km^2 scale.

There were several reasons why the data were prepared at 1-km^2. First of all it allowed for a better approximation of the regional geological interpretation into discretized cells. It also facilitated matching discrepancies between formation data along State boundaries. Southwest regional data submitted to previous NATCARB Atlas versions were generated as a 1 km^2 points before reformatting them to the predefined 10 km^2 polygon cells. Keeping the 1 km^2 scale assured continuity in the data generation methodology. A final reason was that the Colorado plateau area was small enough to allow us to work at such a relative fine scale. The intermediary data file sizes were not that too large to become an obstacle to manage the data workflow.

To facilitate equidistant 1 km sample spacing across state boundaries, the NATCARB 10 km^2 saline polygon template was subset to the polygons belonging to the four participating states only. From these polygons a 1 km^2 base raster was created, preserving the NATCARB Lambert Azimuthal Equal Area projection (Appendix 1). All of the other grids created during the capacity-calculation process were snapped to this base ensuring that the centroids of the grid cells representing different attributes were all exactly geo-located. This procedure allows an exact match by location during the spatial joining of point-data attributes extracted from the grids. Using a uniform grid based on a single projection also ensured that each record of the merged state formation databases represent exactly 1 km^2. It also prevented mismatches of the grids at the state lines. Taking care of the projection at the end of the workflow would have introduced errors in the variables for which the area was a contributing parameter, i.e. all volumes. Establishing a common projection at the onset of the project and having a base dataset to snap all project-derived grids greatly facilitated the data processing workflow.

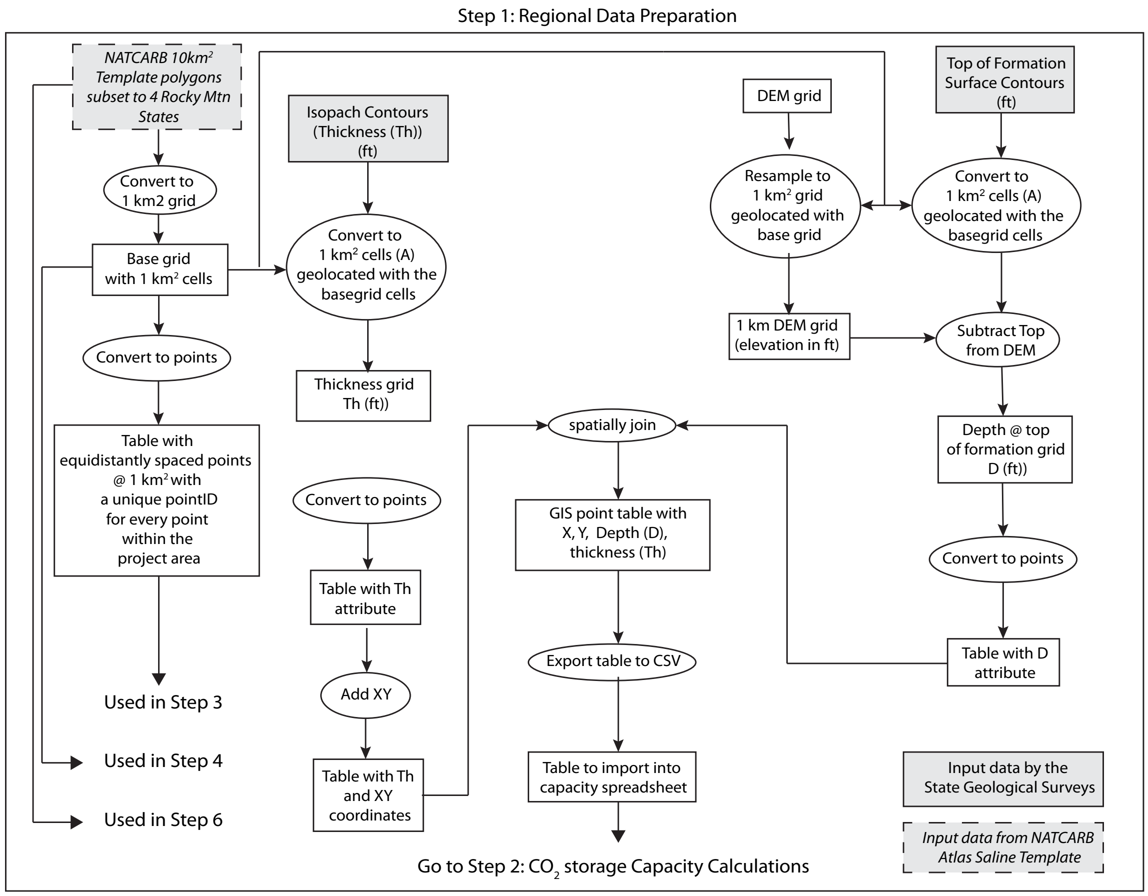


Figure 1: Workflow step 1: Regional data preparation

The base raster also facilitated solving edge matching formation data across state boundaries. Edge matching is a GIS procedure used to align features along the boundaries of two separate data sets. Associating the unique ID number of each 1 km^2 cell with the 1 km^2 GIS capacity data records allowed for summarizing the CO$_2$ storage capacity numbers over all the saline formations or over a selected subset after merging all the 1 km spaced capacity records of the individual formations into a single feature class.

Before the overburden data could be derived from the top of formation data, a 1 km DEM grid - also geo-located with the base raster – was required as well. The University of Utah did the preparation of the base raster while the DEMS were prepared by the state surveys.

b. Generating discretized thickness and overburden (depth) data

Spatially discretized thickness-of-formation and depth-of-the-formation attributes were obtained by converting the isopach and the top of formation contour data to 1 km grids geo-located to the base, raster layer using standard GIS techniques (figure 1). Several techniques were used by the different surveys. Subtracting the top of formation raster from the DEM, generated a grid with depth of formation values.

The accuracy of this depth grid depends on the accuracy of the interpolation of input well data and the generalization of the DEM grid, which was resampled from higher spatial resolution cells to 1 km^2 cells. This procedure was performed for each of the formations of interest, mainly by the state surveys and occasionally with cooperation of the University of Utah. NM was the exception to this procedure. They used the data attributes available in their state well records database and interpolated the thickness and top of formation straight to a terrain model, skipping the contouring process.

The thickness of the Weber Formation is the most uncertain of the three main, deep-saline formations. It is stratigraphically the oldest formation and occurs at great depth. Not many wells penetrated the entire Weber Formation. The deepest top-of-formation-depth was interpolated in the Unita Basin at over 35,000 feet. At the Craig project site, the Weber was deeper than predicted from adjacent logs and geophysical data. Because of overall drilling-cost overruns, the drilling was stopped before reaching the Weber Formation.

c. Converting the thickness and depth data to database records:

Both the depth and thickness, grid-cell values were converted to a point feature dataset. This created fairly large database files. These two attributes were combined into a single table using a join-by location operation. Only records for which both attributes were present were kept. After X and Y coordinates were explicitly added as fields to the database containing the joined depth and thickness values, the database was exported from GIS to a comma-delimited text file, file format which allows for easy interchange of the data with other software packages.

3.3.2 CO_2 Storage-capacity calculations

a. CO_2 density calculations:

The text file generated at the end of step 3.3.1.c was copied into the EGI capacity Excel spreadsheet (EGI capacity calculation spreadsheet), which contained the CO_2 density-calculation macro (Han and McPherson, 2008). The main inputs for the macro are temperature and pressure (Figure 2). These attributes are derived from the depth values in the text file using a certain geothermal and pressure gradient. The geothermal gradient was generally the same by basin, except for UT who applied different gradients for different formations. In the Uinta Basin one gradient was used for the Dakota and the Entrada and another for the Weber formation. Colorado spatially interpolated the gradient derived from bottom hole temperature data. Once temperature and the pressure values at the top of the formation were calculated using the spreadsheet formulas, the CO_2 density values were generated by running the Visual Basic macro.

b. CO_2 capacity calculations:

A separate worksheet was developed in which all of the derived attributes (X coordinate, Y coordinate, temperature, pressure, depth, thickness and CO_2 density) for all the records were copied into. Before calculating the CO_2 volumes a few formula-based fields for additional attributes were generated (volume, pore volume and CO_2 mass). The CO_2-density, macro output was converted to metric units so the CO_2 volume could be generated in metric tonnes, the NATCARB Atlas reporting unit. The volume of each cell was generated by multiplying the area (1-km^2 for each data point, defined by the raster cell from which the attributes were extracted) by the thickness of the formation at that cell. Multiplying the cell volume by the porosity, generated the pore volume. The CO_2 mass was obtained by multiplying the pore volume by the CO_2 density. The CO_2 storage capacity volumes at the 1 km scale were calculated by applying the low (0.51%), medium (2%) and high (5.4%) efficiency factors to the CO_2 mass. This worksheet contains all the data from which a new point feature class can be generated in GIS.

Although the spreadsheet with the formulas was provided to the surveys, not all of them followed the template, or some made changes to them to suit their data. Before the data could be imported into GIS, it was necessary to generate a common set of field names that were exactly the same for all the formation data files within a state, as well as in files from the different states. This was necessary in order to merge the formation data from the different states into a single formation point database. Having a different set of fieldnames for the different formations would prevent merging the across-state-integrated-formation data into a single GIS feature class. Utah’s data, which were provided in geodatabase feature classes by formation, still needed to be modified to adjust the field names. Because adjusting the fieldnames outside the GIS environment is a faster process compared to applying GIS database techniques, the records were exported to a CSV file, modified in a spreadsheet and then reloaded into GIS.

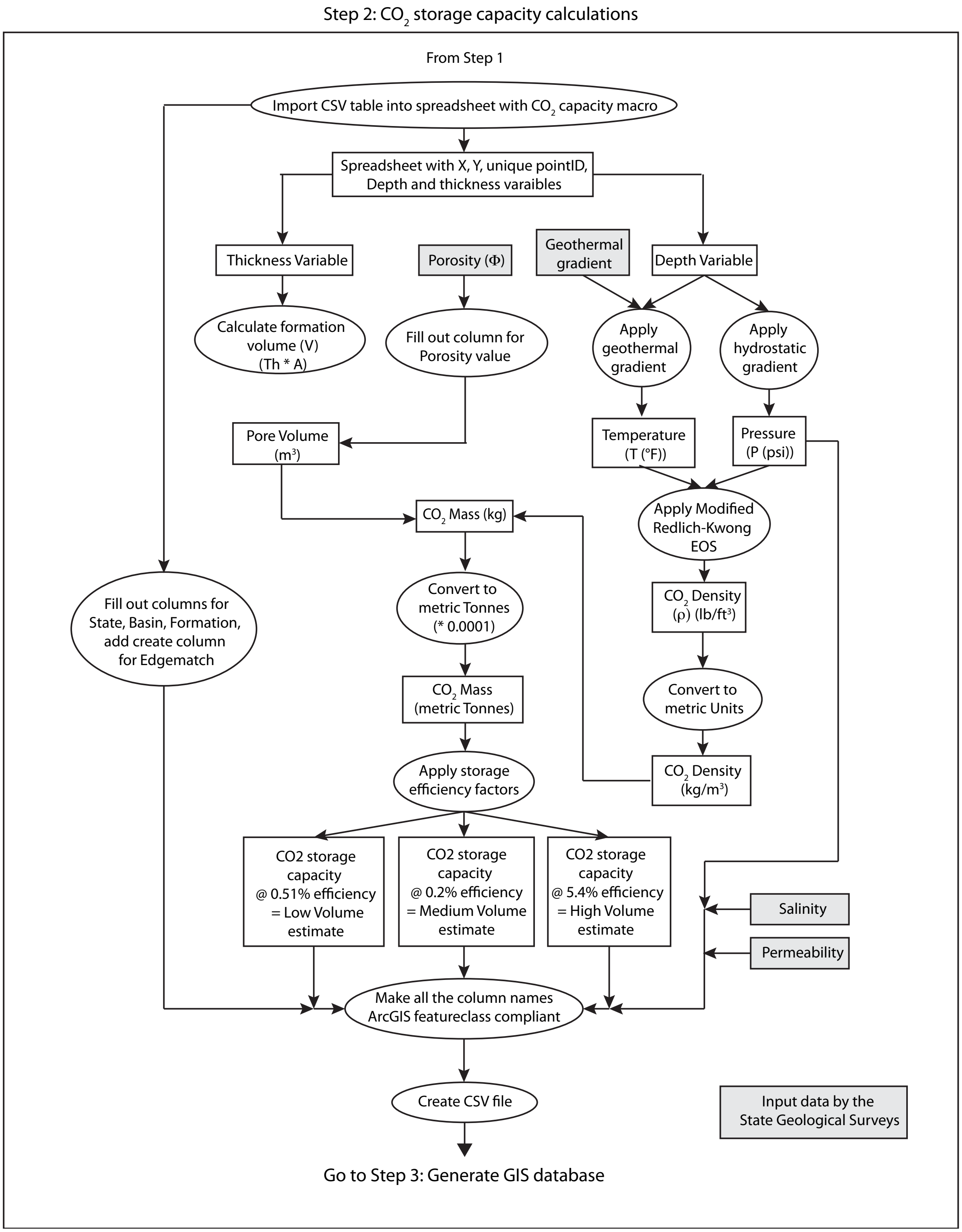


Figure 2: Workflow step 2 – CO_2 Capacity calculations

c. Formation contour at 3000' depth:

Finally, to be able to format the CO_2 capacity numbers into the pre-defined NATCARB Atlas format, a polygon representing the outline of the formation at 3000' depth was required. Some State Geological Surveys provided these contour lines, other only provided the 1 km spaced points and the limiting extent was screen digitized by University of Utah.

3.3.3 Creation of GIS CO_2 storage capacity point database.

a. Importing the 1-km^2-CO_2-capacity data into GIS

- Point data by formation:

An additional field was added to the database to indicate whether the record represented an original data point generated by the State Geological Surveys, or if it was added to fill in missing data points. The binary field values were marked as 'N'' for an original data record, or 'Y' for the records representing points created to enforce spatial data continuity. Another field was added by spatially joining the GIS point data to points converted to the 1-km-spaced base, Rocky Mountain raster grid. Doing this made it possible to associate a unique point-ID to each formation record (Figure 3). This point-ID was consistent for all formations for which records at the same locations are available, i.e. for cells for which there are data in multiple stratigraphic formations. The unique point-ID was added by spatially joining the 1-km-spaced-CO_2-capacity data to the points that were converted, base-raster cells.

The final step consisted of quality checking the data. Different test are required for numeric defined fields and text defined ones. The numeric tests relied on simple methods such as making sure the magnitude and the data ranges were within expected values. We also gridded the different numeric parameters to check for discontinuities in the data. Magnitude inconsistencies often indicated parameter unit problems requiring unit conversions of the values. Negative thickness values resulting from interpolating geological conditions were eliminated. The interpolation algorithm generated negative thickness values between the lines representing contours of zero thickness. Data records with a depth at the top of formation less than 3000' were eliminated too. The text-defined, database fields were checked for spelling consistency across all records.

Step 3: Creation of CO2 capacity point GIS databases

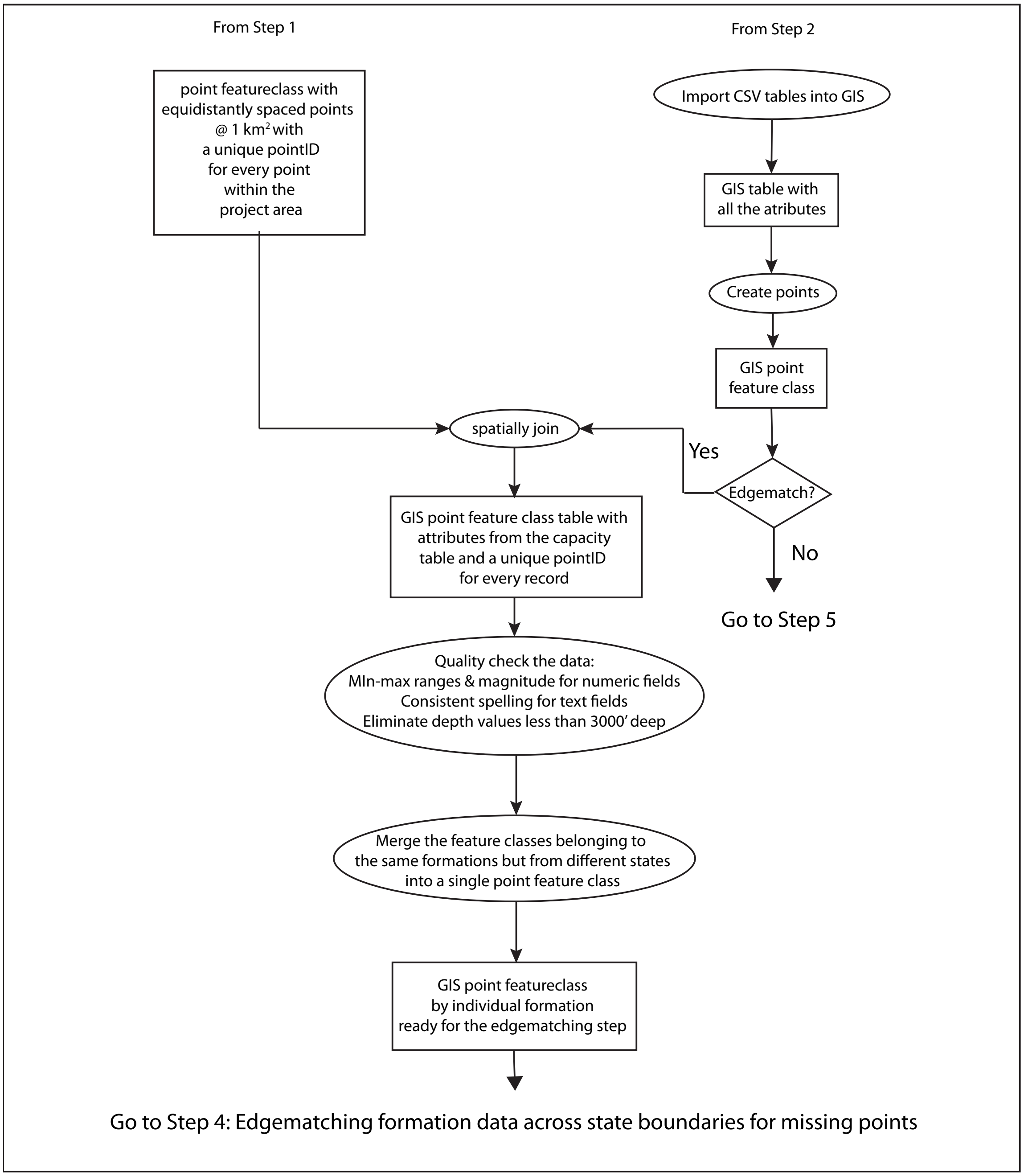


Figure 3: Workflow step 3 - Creation of quality-checked, GIS-CO$_2$-capacity database with a set of database fieldnames consistent across the saline formations for the 4 Rocky Mountain States.

- Formation polygon outlines at 3000' depth:

Besides a database with 1-km-spaced points for each deep saline formation, a polygon outline of these formations at the 3000' cut-off depth needed to be prepared for use during the edge matching process, Further, this was necessary to calculate the 'resource_area' field for the NATCARB saline-atlas field at the 10 km^2scale. These formation outlines were created by combining polygons provided by either the State Geological Surveys or the outlines that were screen digitized around the point locations. For formations with multiple, spatially-separated polygons, the single part features were combined into a multipart feature so that each formation is represented by a single record in the formation-outline, merged database.

3.3.4 Edge matching formation data across state boundaries:

Spatial edge matching problems occur at borders between data sets. This problem most commonly takes place when line or polygon features have to be joined. In this project superimposing administrative state boundaries on geologically continuous data created these artificial edges. Because the 1-km points in the formation data sets for this project actually represent a discretization of a data parameter in the area (polygon) of the formation below 3000' depth; issues related to spatial continuity need to be addressed.

Four different situations needed to be dealt with. The easiest one to correct was the one where duplicate points existed. There were a few instances where a narrow strip of cross-boundary data points were included in the records of both adjacent states. Rectifying this problem required deleting the one point of duplicated spatial records: the points within the state of the survey that created the data were maintained; those that crossed into the neighboring state were removed.

A second crossover problem happened where points were located in a neighboring state whereas the state that should have generated the point did not have a data point at that location. In this case, the depth and pressure parameters were kept but the porosity and geothermal gradient was adjusted to correspond to the rules and values set by the state in which the point is located. This required recalculations of the CO_2 capacity.

Dealing with missing records was more difficult to handle. A first cause for missing data points along state lines can be attributed to each state using their own state outline to define their data. Small spatial discrepancies along the state boundaries caused some of the 1 km points not to be included in the 1 km^2 data set of either state. Although the missing points represent a 1 km gap, this does not necessarily imply that the state boundaries are offset by the same amount. Having what should have been a common state boundary line instead pass just on either side of the 1 km grid centroid, will cause the exclusion of the point in the data sets of both states resulting in the gap when the points are merged. This problem could have been prevented by providing a topologically correct, state boundary file containing the outlines of the four states involved at the onset of the project.

Finally, a few problems occurred where there was an offset of the 3000’ depth contour at state borders (Figure 4). This problem was most likely caused by the surveys only using their state’s data as the source for their interpretations, while excluding data points that were across state boundaries. By using only single-state-source data, extrapolation to the state boundary was based on best-knowledge, ancillary information, rather than actual data just across state boundaries. Including data from wells across state lines could have resulted in a tighter interpretation at the boundary while also reducing uncertainty. The range of the offset of the 3000’ contour line was in the order of a few kilometers where ancillary basin data were used to generate the depth and thickness maps. The offsets were much larger where 1-km-spaced data were created by computer based interpolation between wells with known records only, and not manually extrapolated to the 3000’ depth boundary using best knowledge practices. In this situation matching up the 3000’ depth contour line involved discussions between the partners of each involved state.

After agreeing on how to spatially match the data across the state boundary, the polygon boundary of the area was edited to reflect the modification. This polygon was used to extract all the equidistant 1 km-spaced points from the Rocky Mountain base grid that was created at the onset of the workflow. This new database contained location records for the points generated by the State geological surveys as well as for the missing points. The missing points at this step have no data values for any of the parameters besides the XY coordinate locations and the unique point-ID number. A new binary field, representing either an existing data point or a new data point was added to this newly created table. Joining the formation points subset of the basin (where the edge matching is required) to the newly created table using the common field (the base layer point-ID) allows for updating the just-created, binary-valued field in the ArcGIS field calculator. The points that were already processed will have a ‘N’-value while the ‘null’-value for the points for which capacities were replaced with a ‘Y’-value. A new raster was created from the binary values to later be used as a mask to extract the unknown thickness and depth data. Temperature can be derived from the depth values when a constant geothermal gradient was used but where the geothermal gradient changed spatially, the temperature data for the missing points were interpolated as well. Just as with all other grids generated during the workflow thus far, this binary mask was snapped to the base grid created at the onset of the workflow. Attributing the unknown points with the state in which they plot was the last preparatory step required before generating parameters for the unknown data points. One state used spatially varying porosity values, but the edge matching procedure of the formation did not require generating additional points.

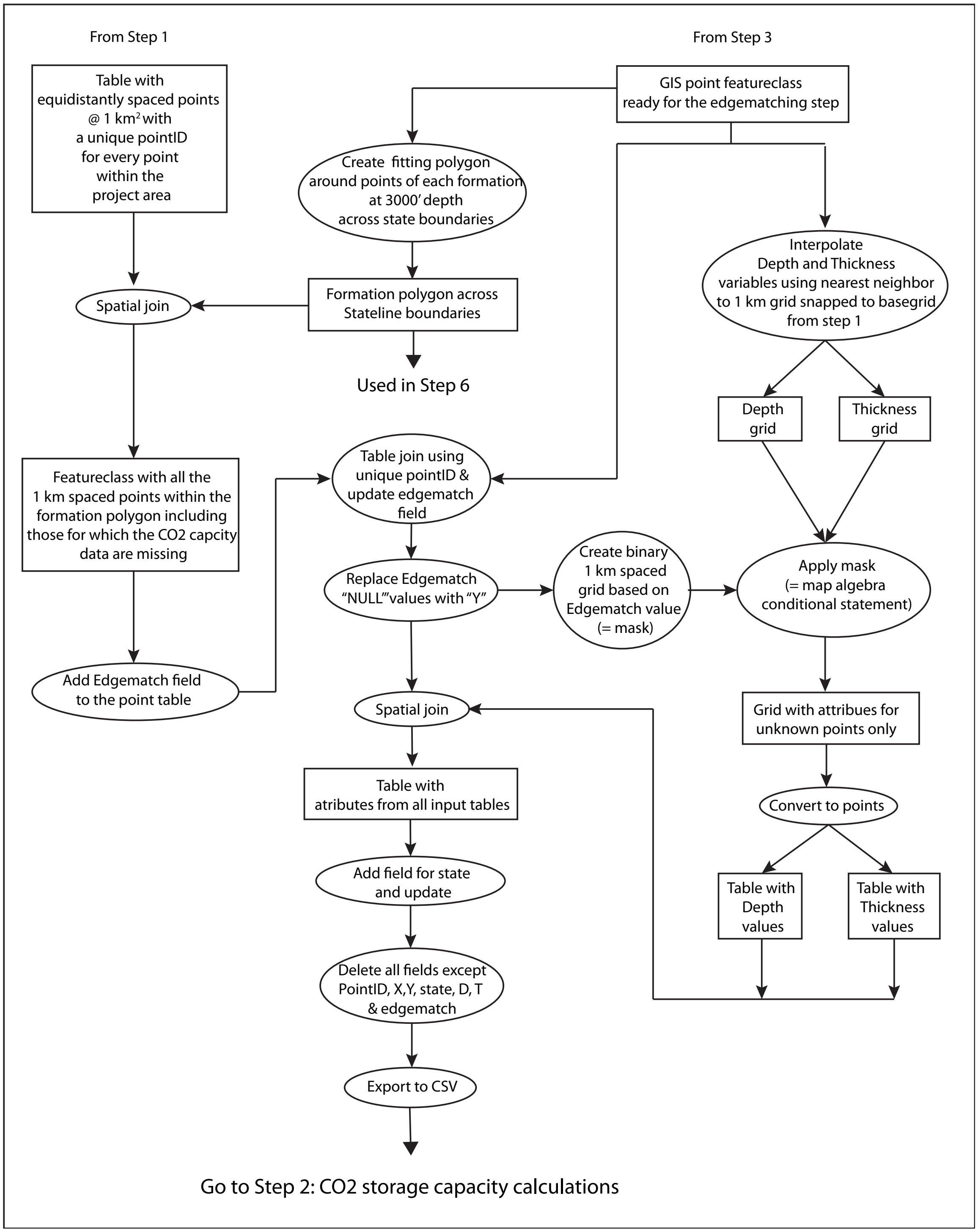

Step 4: Edgematching formation point data @1 km² across State lines

Figure 4: Workflow Step 4 – edgematching formation data across state boundaries

Depth and thickness values were derived at the missing locations by interpolating the values, using a natural neighbor algorithm, from the existing data provided by the state geological surveys. Both output grids were geolocated with the base grid and the values of the new points were extracted using a raster-calculator, conditional statement invoking the binary mask. The retained points, extracted from the interpolated parameter grids, were spatially joined with one another as well as with the table containing the unique point-ID variable, the associated state code and the XY coordinates. This table combining all the parameters was exported to a CSV file and manipulated in the capacity spreadsheet in a similar manner as described under step 2 of the workflow. The porosity and geothermal gradient were assigned following the numbers of the state in which the point was located. Once the worksheet was structured the same, having all the parameters calculated and fieldnames assigned, (as the spreadsheets processed with the points provided by the state geological surveys), it was loaded into ArcGIS and merged with the existing point data for that formation.

Besides problems with the spatial data continuity, the state-by-state approach resulted in data-value discontinuities across state boundaries as well. Their details will be reported in the section describing the actual data. Generally the data-discontinuity problems can be attributed to states using different, single-valued parameters for porosity and the geothermal gradient. Or, some states set a constant value for all their records in a certain formation for the area covering their state while others used a spatially varying one (ex. porosity and geothermal gradient). Changes in thickness and depth across state boundaries occurred because the bounding basal and top, strata were not precisely defined ahead of time (e.g., Entrada). In one instance, a different constant geothermal gradient was used within a state for different formations within the same sedimentary basin. Not all states provided data for the parameters that were not required to calculate the CO_2 storage capacity (permeability and salinity).

The Utah Geological Survey created a web-based, ArcGIS online site to which the other surveys were invited to upload their preliminary contour data with the anticipation this could be used by the participating states to compare their deliverables to those in adjacent states and make adjustments if needed. The UGS did adjust their Entrada maps after noticing CO had used different layers to constrain the formation. AZ uploaded their data as well. NM did not generate contour maps, only terrain maps, and did not make use of this tool. As a result, the data continuity along New Mexico's stateliness was more difficult to match than along the other borders.

3.3.5 Integration of the regional, 1-km-spaced Rocky Mountain-CO_2-capacity GIS database

After the same database structure was created for each formation table, the quality control was completed. The points for each formation were edge matched across the state boundaries, and all the properties of corresponding fields in the different formation databases were defined exactly the same, i.e. enforcing data integrity on the database. Then, the tables for all the formations were merged into a single, point-feature class containing all the data records for all the formations (Figure 5).

The CO_2 capacity numbers - as well as others such as thickness and pore volume - can then be summarized in tables by state, formation and/or sedimentary basin. The total capacity numbers can also be summed for each 1-km point using the unique ID number that was extracted from the base grid and associated with each data point. The 1-km data can be summarized either by a subset of the formations or by all of them. The 1-km^2 cell summaries allow for generating maps illustrating the spatial variability of the parameter.

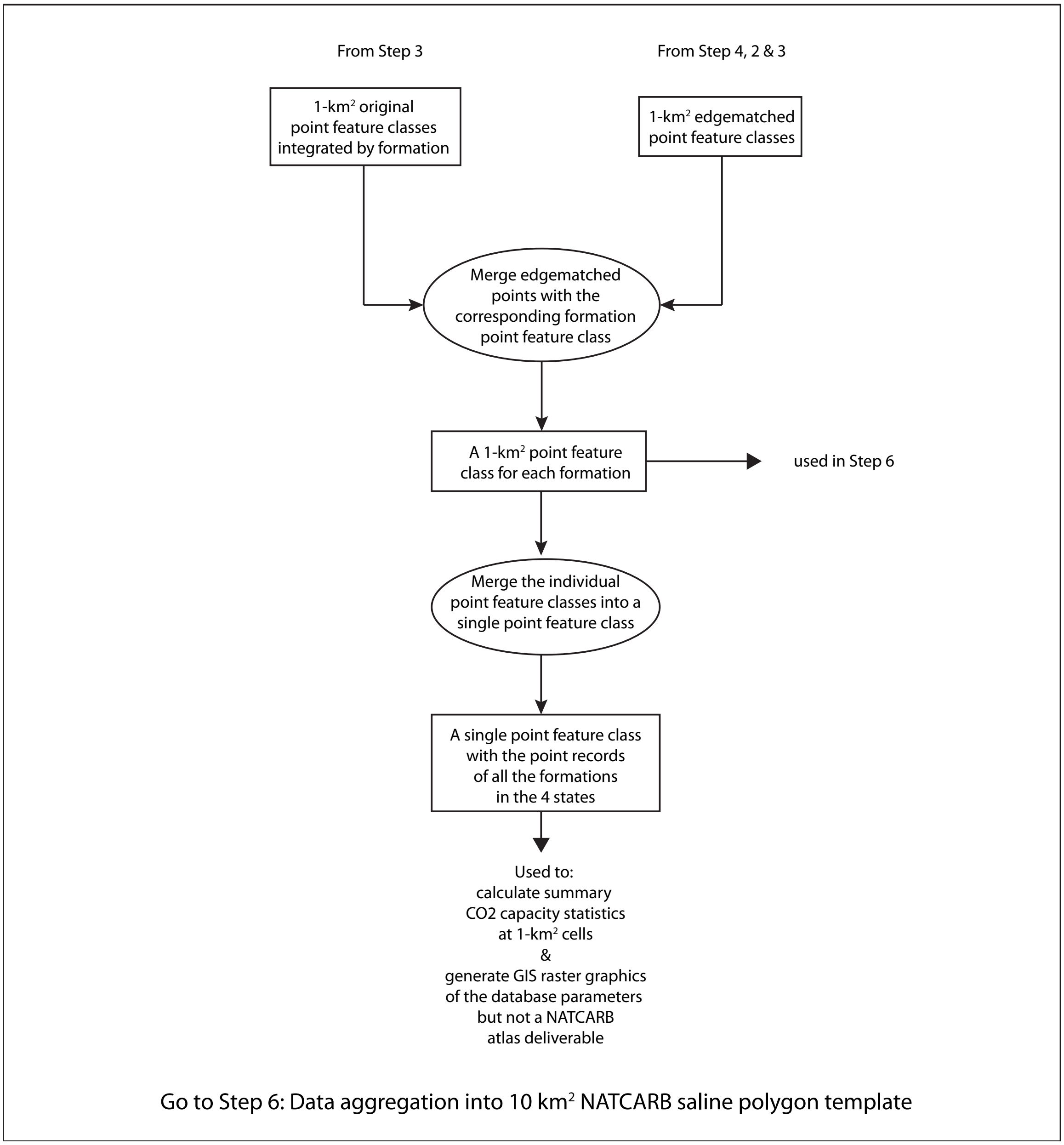

Step 5: Compiling the RMCCS saline GIS database at 1-km^2 scale

Figure 5: Workflow step 5 – Compiling the integrated, saline-formation CO_2-capacity database at 1 km^2 scale.

Besides several problems inherent to having the states generate their data (mostly independently from one another), additional data issues exist. Some are related to extreme simplification of the geology (caused by lack of better data) such as using a single porosity value for an entire formation. This disregards geological 3D spatial heterogeneity and anisotropy. The same argument can be made for the thermal gradient. Utah tackled the single porosity problem by interpolating known porosity values from well data across the Weber and De Chelly Formations within the sedimentary basin. Colorado used a similar spatial approach for the geothermal gradient. However, the data end-user has no indication about the reliability of the generated data. The project team had planned to address this by generating a well-density parameter for each 1-km^2 cell as well as a distance to nearest cell containing source well data. Since this study is using spatially continuously varying data, concepts of spatial autocorrelation indicate that data generated in a cell closer to a cell with existing data is most likely more reliable than data in cells further away from reported data. These uncertainty indicators were not incorporated.

Another uncertainty issue that should be addressed to gauge the data reliability is a quantifier of the quality of the original input data, especially where wells are clustered. Not only were generalizations made under those circumstances but the end-user does not know which criteria were used. Since the data for this project were derived from databases compiled over time and for which the input data were generated by many geologists each using their own standards, it is not known how well the source data were screened for inconsistent values.

Although NETL requests saline data in the CO_2 capacity Atlas be included, most of the states did not provide salinity data. This information is often not readily available, or included in the databases they used as their source. This could be remedied by including a layer indicating USDW data in the Atlas. Just as with the uncertainty indicator(s) there was not enough time to pursue this within the timeframe of the project.

Permeability data are requested by NETL as well. This parameter generally is more heterogeneous and anisotropic than the porosity parameter. Since the permeability value is also not required to calculate storage capacity but comes into play to model injectivity, most surveys did not provide permeability data because they did not want to over-generalize. And, reliable permeability data is difficult to obtain from the public domain. Even industry does not have good datasets for permeability variations.

3.3.6 Aggregating (upscaling) the data into 10-km^2 NATCARB predefined polygons

Aggregation of the 1-km-scaled, formation point data into predefined 10 km^2 cells is required to make the capacity data compliant with the NATCARB carbon sequestration Atlas for saline-formations-data dictionary (Appendix 2). The 1-km^2

data for each formation were processed by themselves before merging all the results into the NATCARB template. The first step consisted of spatial joining each 1-km^2-formation-point-feature class with the NATCARB saline-10K template subset to the four-state region (Figure 6). This procedure aggregated all the 1-km points located within a 10-km^2 polygon into a single value for the different parameters. During this step, the fields and the field contents belonging to the 10K template are not modified. Most of the 10-km^2 attribute fields contain 'Null'-values. The COL_ROW number is populated with a unique 10K polygon ID, comparable to the unique pointID used for the 1-km^2 points. The attributes of the 1-km^2-formation-point, feature class were summarized according to a set of merging rules. The numeric parameters were averaged (Depth, Thickness, Temperature, Pressure, Porosity, Salinity, Permeability and CO_2-density) except for the volume- (volume, pore volume) and CO_2-mass related parameters (CO_2-mass, CO_2-mass at 0.51%, at 2% and at 5.4%), which were summed. The first occurrence was extracted for the fields defined as text (basin and formation). Fields not serving any purpose at the 10 km^2 level scale were dropped during the aggregation (1 km pointID, state, edgematch indicator, X and Y coordinates). The basin parameter is not included in the NATCARB database dictionary, but was kept for internal use.

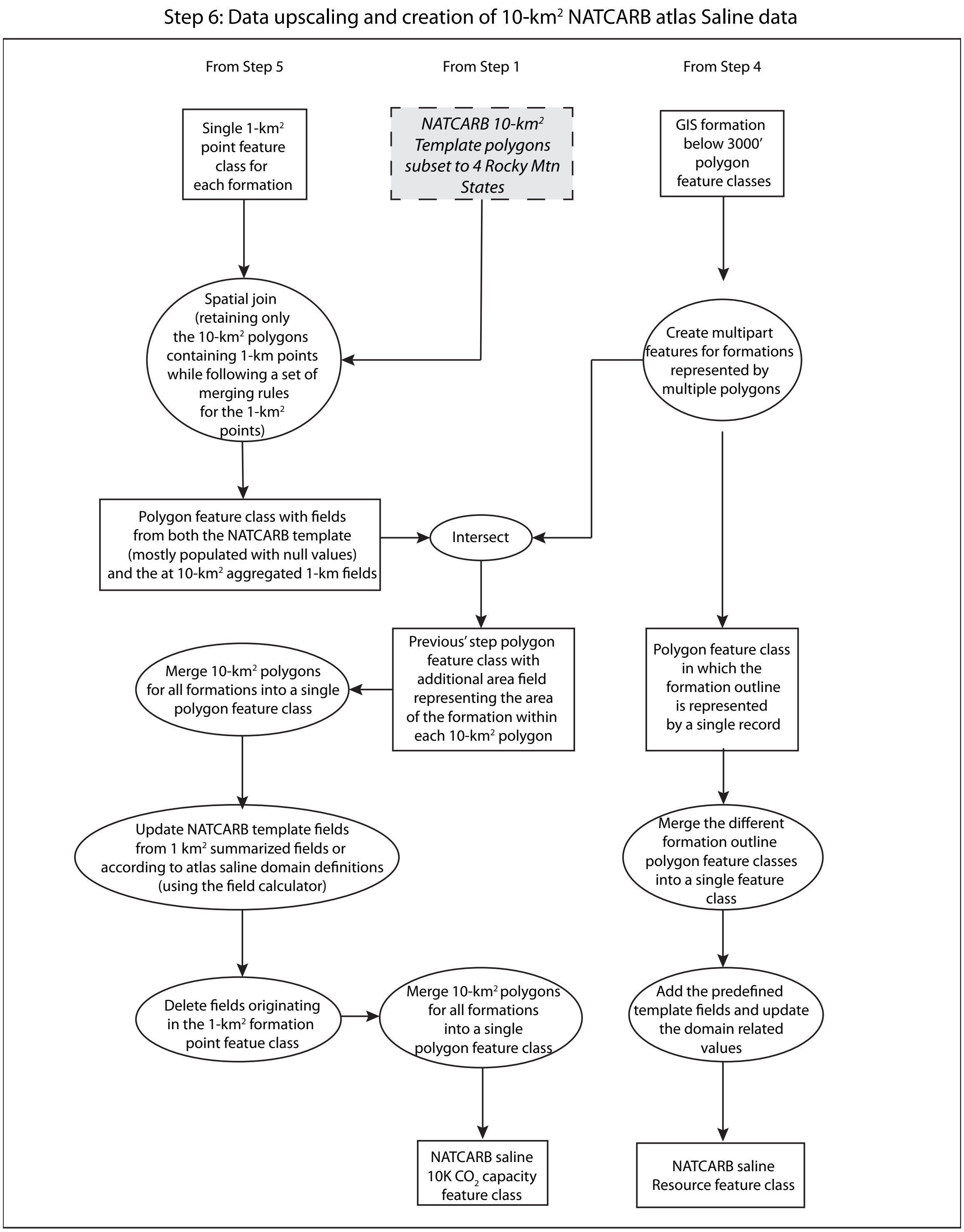


Figure 6: Workflow step 6 - Upscaling the data to 10-km² and NATCARB compliant saline data creation

For each formation, the output of the spatial-join procedure was intersected with the corresponding formation polygon 3000' depth outline. This intersection process calculated the area of the formation within each 10-km² polygon and stored it in a newly added area field. For most polygons this number will be 100,000,000 m^2 corresponding to the 10 by 10 km area. Near the outer edge of the formation or where there is an interior gap in the formation data, this number will be less.

Since all the 10 km^2 formation tables with the summarized 1 km^2 data and the updated area numbers had the same database structure, they could be merged into a single, new-feature-polygon class that now contained data for all the formations at the upscaled 10 km^2 level. All the NATCARB template fields are still populated with null values however. Using the field calculator, those template field values were updated by extracting the values from the corresponding statistically summarized data fields. After the NATCARB-template, null values were replaced with the information from the statistically summarized fields, the latter set of fields was removed. Finally, the up-scaling to 10-km^2 data was completed by populating the fields that have a single value for all the records, for example the RSCP field, ARRA_PROJECT field and the geodatabase-domain-related fields.

Data preparation done during the compilation procedure of the 1-km^2 data resulted in 7 structurally completely consistent data sets. This would have allowed the python script to easily handle the upscaling steps. However, writing this script would have taken longer than repeating the process for each formation using ArcGIS's GUI interface. Ninety percent of the University of Utah's Atlas data task time was spent in the following tasks:

1. Guiding, assisting and coordinating the surveys near the end phase of their data preparation time,
2. Integrating all of their 1-km^2data, including data-problem tracking and solving,
3. Developing the workflow to format the data into a common database structure, including edge matching the data across state boundaries.

Aggregating the data to make the NATCARB Atlas compliant and reporting took the remaining 10%.

4. Rocky Mountain Carbon Capture and Sequestration Project CO_2 capacity data

Geological surveys of the four partnering states delivered data for the three deep saline formations (Cretaceous Dakota, Jurassic Entrada and Permian Weber) occurring mostly in the northern half of the Colorado plateau, as well as four Paleozoic stratigraphic equivalent formations further to the south (Cedar Mesa, De Chelly, Hermosa and Leadville formations). These seven formations are occurring in 5 different basins: the Uinta basin and the Piceance/SandWash basins in the north; and the San Juan, Black Mesa and Paradox basins in the south. A total of 14 input data sets containing various stages of CO_2-capacity calculations were sent to the University of Utah in 4 different data formats: spreadsheets, ArcGIS file geodatabases, ArcGIS map package with raster data and shapefile depth and thickness contour lines (Table 2).

Formation	Basin	AZ	UT	CO	NM
Dakota	Piceance/SandWash			xls	
	Uinta		gdb		
	San Juan				xls
Entrada	Piceance/SandWash			xls	
	Uinta		gdb		
	San Juan				xls
Weber	Piceance/SandWash			xls	
	Uinta		mpk, xls		
Hermosa	San Juan				xls
De Chelly	Black Mesa	shp			
	Paradox		gdb, xls	xls	
Cedar Mesa	Black Mesa	xls			
Leadville	San Juan				xls

Table 2: format of submitted data to the University of Utah: gdb = ArcGIS geodatabase, mpk = ArcGIS map package, shp = ESRI shape file, xls = MS Excel.

These different files, all containing slightly different information, were reformatted into a common database structure. Data not delivered in spreadsheets were the most difficult to use in determining methodology problems because the calculations were not, or were poorly, documented. A few cases related to unspecified, variable units had to be dealt with. And, in two other situations the projection of the data was not the requested, Lambert azimuthal equal area. This required a fair number of recalculations to make the data fit the 1-km-equidistant grid laid out for the entire region, and across the state boundaries. After reformatting the point data into a common ArcGIS database, the state-boundary-crossing-formation datasets required edge-matching-problem corrections. Only then, could they be prepared to conform to NETL's smaller-scale, Carbon-sequestration-Atlas data structure.

Most files had records for depth and thickness either in the spreadsheet or in the feature class database. The only exception was the Arizona De Chelly data, which were not originally part of the to-be-submitted data. Because of a small miscommunication problem, the data were not shared until very late in the workflow process. The AGS sent two shapefiles, one with thickness contours and one with depth contours. These files were re-projected to the Atlas Lambert azimuthal equal area projection before being converted to grids from which the depth and thickness values were extracted at the 1-km^2 scale. These parameters combined with the porosity values that were provided and a geothermal gradient, allowed for the data to be processed in the capacity spreadsheet and structured according to the other data.

The porosity values together with the formation thickness data provided the bulk storage volume. Most data were processed with a single porosity value set by basin in each state. Most data sets also provided a minimum and maximum porosity value, listed in Table 3, but only the medium values were incorporated in the storage capacity calculations. The only exception to this method was the Weber calculation in the Uinta basin, where the porosity value was interpolated and depended on the location. The results of the porosity test of core from the single site characterization well, RMCCS State #1, were not yet available when regional CO_2 capacity estimates were generated and are thus not included in the analysis.

Table 3: Rocky Mountain Carbon Sequestration Project deep saline porosity values:

		Porosity (%)		
		Min	Average	Max
Dakota	CO	-	10.0	-
	UT	2.0	12.0	22.0
	NM	2.5	6.3	13.2
Entrada	CO	-	15.0	-
	UT	8.0	16.0	24.0
	NM	7.4	9.6	22.5
Weber	UT	Varies spatially between 1.12 and 22.45 with an average of 6.22		
	CO	-	8.0	-
Hermosa	NM	3.0	9.9	14.2
De Chelly	AZ	-	14.3	-
	UT	-	20.0	-
	CO	-	10.0	-
Cedar Mesa	AZ	2.0	4.6	8.04
Leadville	NM	1.0	4.0	7.0

Applied geothermal temperature gradients generally varied by state and by formation, although in most cases the different gradient was used in the same basin for different formations (Table 4). Colorado made their geothermal gradient spatially dependent by deriving the gradient from temperatures measured in well data located across the state. The interpolated gradient data were extracted from the grid, which was geo-located to the base grid and added as an additional column to the spreadsheet.

Table 4: Rocky Mountain Carbon Sequestration Project geothermal gradients used to derive temperatures at top of formation depth for deep saline CO_2 storage formations

State	**Basin**	**Formation(s)**	**Gradient[*]**	**Temp @ depth Formula = Surface temp (F) + gradient**
AZ	Black Mesa	Cedar Mesa De Chelly	13.5°C/km	75 + (0.0074 * D[**])
CO	Piceance/ SandWash	Dakota Entrada Weber	Spatial dependent	55 + (gradient in the 1km^2 cell * D)
	Paradox	De Chelly		
	San Juan	Dakota		
UT	Uinta	Dakota Entrada	25°C/km	55 + (0.0138 * D)
		Weber	20°C/km	55 + (0.0115 * D)
	Paradox	De Chelly	20°C/km	55 + (0.0115 * D)
NM	San Juan	Dakota Entrada Hermosa Leadville	47°C/km	61 + (0.026 * D)

[*] Geothermal conversion factor from °C/100m to °F/100ft: 0.549 (Klett 2005)
D[**] = depth in feet

The New Mexico Bureau of Geology and Mineral Resources provided salinity and permeability values for the San Juan basin formations (Table 5). Other states did not contribute these parameters.

Table 5: Salinity and Permeability data fro the NM deep saline formations

State	Formation	Salinity (TDS)	Permeability (mD)
NM	Dakota	25000	0.83
	Entrada	35000	0.09
	Hermosa	85000	0.2
	Leadville	35000	-

CO_2 capacity numbers grouped by formation but separated by state and sedimentary basin are listed in Table 6. Figure 7 shows the spatial distribution of he total capacity numbers summed over all of the formations at the 1-km^2 data-distribution scale. The total, calculated-CO_2-storage-capacity for all seven formations (using the average porosity for most data) varies between 13.6 and

143.7 billion metric tonnes depending on the efficiency factor. For the three major, deep-saline formations the values vary between 9.8 and 104.0 billion metric tonnes. The CO_2-capacity volumes summarized at the 10-km^2, Atlas scale are the same as the larger scales. However, at the larger scale, they cannot be broken out by state or sedimentary basin, only by the resource formation. The CO_2-storage-capacity volumes summarized by formation are listed in Table 7.

Table 6: Rocky Mountain Carbon Sequestration Project deep-saline, CO_2-capacity numbers derived from the 1 km^2 scaled points:

				CO2 Storage Volume (metric Tonnes)		
State	Basin	Formation	Area (km^2)	Low Efficiency (0.51%)	Medium Efficiency (2%)	High Efficiency (5.4 %)
CO	Piceance_ Sandwash	Dakota	28,522	482,624,867	1,892,646,535	5,110,145,645
CO	San Juan		3,214	68,252,705	267,657,665	722,675,695
NM	San Juan		19,599	172,502,878	676,481,873	1,826,501,060
UT	Uinta		28,834	507,104,513	1,988,645,149	5,369,341,904
CO	Piceance_ Sandwash	Entrada	30,052	1,393,361,516	5,464,162,810	14,753,239,586
CO	San Juan		4,595	127,397,634	499,598,566	1,348,916,127
NM	San Juan		16,511	300,019,280	1,176,546,181	3,176,674,688
UT	Uinta	Entrada-Navajo	29,989	4,857,039,869	19,047,215,174	51,427,480,970
CO	Piceance_ Sandwash	Weber	15,577	549,361,376	2,154,358,336	5,816,767,507
UT	Uinta		27,789	1,361,192,180	5,338,008,549	14,412,623,083
NM	San Juan	Hermosa	9,444	1,672,530,703	6,558,943,933	17,709,148,619
AZ	Black Mesa	De Chelly	10,053	1,820,718,060	7,140,070,822	19,278,191,219
CO	Paradox		1,934	13,715,122	53,784,794	145,218,943
UT	Paradox		1,579	35,650,148	139,804,502	377,472,155
AZ	Black Mesa	Cedar Mesa	17,139	168,097,713	659,206,719	1,779,858,142
NM	San Juan	Leadville	12,247	42,728,636	167,563,275	452,420,844
			Totals:	**13,572,297,199**	**53,224,694,882**	**143,706,676,188**

Table 7: CO_2 storage capacity volumes summarized by formation

	CO_2 Storage Volume (metric Giga Tonnes)		
Formation	Low Effciency (0.51%)	Medium Effciency (2%)	High Effciency (5.4%)
Dakota	1.23	4.83	13.03
Entrada	6.68	26.19	70.71
Weber	1.91	7.49	20.23
Partial Total:	**9.82**	**38.51**	**103.96**
Hermosa	1.67	6.56	17.71
Cedar Mesa	0.17	0.66	1.78
De Chelly	1.87	7.33	19.80
Leadville	0.04	0.17	0.45
Total:	**13.57**	**53.22**	**143.71**

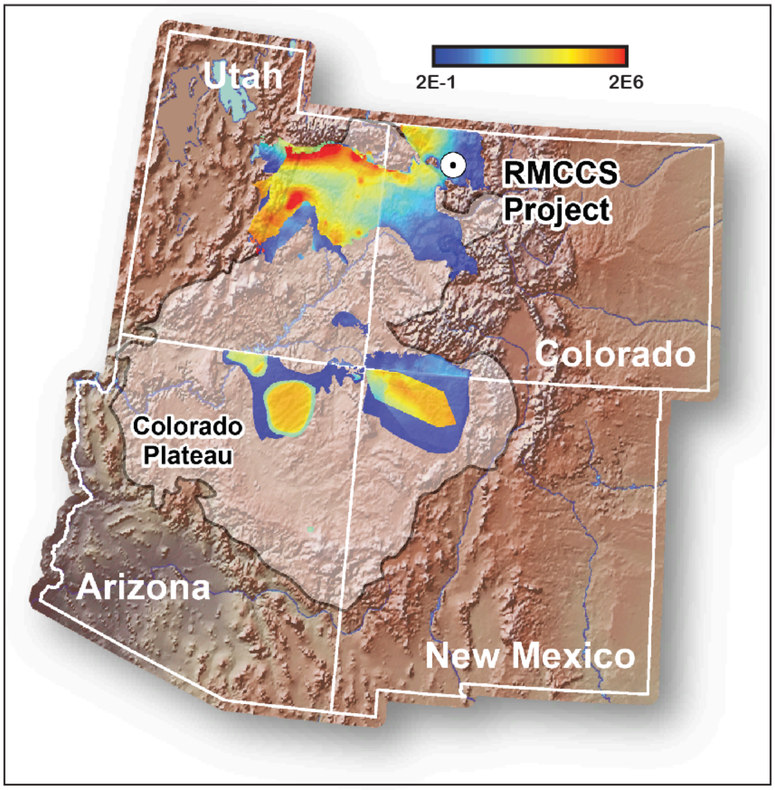


Figure 7: Spatial distribution of the CO_2 storage capacity summed over all 7 formations using a 1-km^2 cell size. The color-bar represents the medium efficiency CO_2 capacity data in metric tonnes.

5. Comparison of 2013 project most promising CO_2 capacity data to previous data for the 3 main saline formations on the Colorado Plateau:

Comparing this project's CO_2 storage capacity volumes to the 2012 data (NATCARB Atlas IV), subset to the Colorado Basin area, indicate the total estimated CO_2 volumes are different (Table 8 and Figure 8). The Entrada Formation CO_2 volumes increased compared to the previous data while the storage capacity in the Dakota and the Weber Formations decreased. A main contributing factor to the increased Entrada capacity is an increase of the area of the Entrada Formation, a direct contributor to the bulk volume. The decrease in the Dakota storage capacity by nearly 50% can be explained by using a porosity value that is up to less than half of the Atlas IV porosity value of 14%. The current project calculations also applied a higher geothermal gradient for the San Juan basin compared to the 2012 data, where a single geothermal gradient was used for all the data in the region the Southwest Partnership was responsible for. A combination of several factors explains the almost 70% reduction of storage capacity in the Weber Formation. The largest contributing factor is the lower average porosity. This study, used an average of 6.9%, which is less than half of the average porosity of 14.9% used in Atlas IV for the same region. The total area and the total available thickness for the Weber Formation in this study are both less than the values calculated for the previous Atlas as well.

The results of this study indicate a potential CO_2-storage capacity for the three main, regional saline formations ranging between 12.9 and 136.8 billion metric tons depending on the efficiency factor (Table 8). When compared to the 2012 Atlas IV data the total CO_2-storage capacity of these three formations decreased by approximately 8%. Including the stratigraphic equivalents, increased the total CO_2 storage capacity between 13.6 and 143.7 billion tonnes. Since not all the equivalent formations were included in the Atlas IV data, a CO_2 storage capacity comparison cannot be made.

Table 8: Difference in CO_2 capacity numbers between 2012 Atlas IV and this project's three main deep saline formations on the Colorado Plateau:

			CO_2 Storage Volume (metric Giga Tonnes)		
	Formation	# of 10 km^2 cells*	Low Efficiency (0.51%)	Medium Efficincey (2%)	High Efficiency (5.4%)
Atlas IV	Dakota	955	2.132	8.360	22.572
	Entrada	595	3.531	13.847	37.387
	Weber	626	4.964	19.468	52.563
	Total:		**10.627**	**41.675**	**112.521**
Atlas V	Dakota	943	1.230	4.825	13.029
	Entrada	964	6.678	26.188	70.706
	Weber	564	1.911	7.492	20.229
	Total:		**9.819**	**38.505**	**103.964**
IV to V Difference (V - IV)	Dakota	-12	-0.901	-3.534	-9.543
	Entrada	369	3.147	12.341	33.319
	Weber	-62	-3.054	-11.975	-32.334
	V - IV Difference:		**-0.808**	**-3.169**	**-8.557**

* Not all cells contain 100% formation at depth; those along the edge of the formation are only partially filled

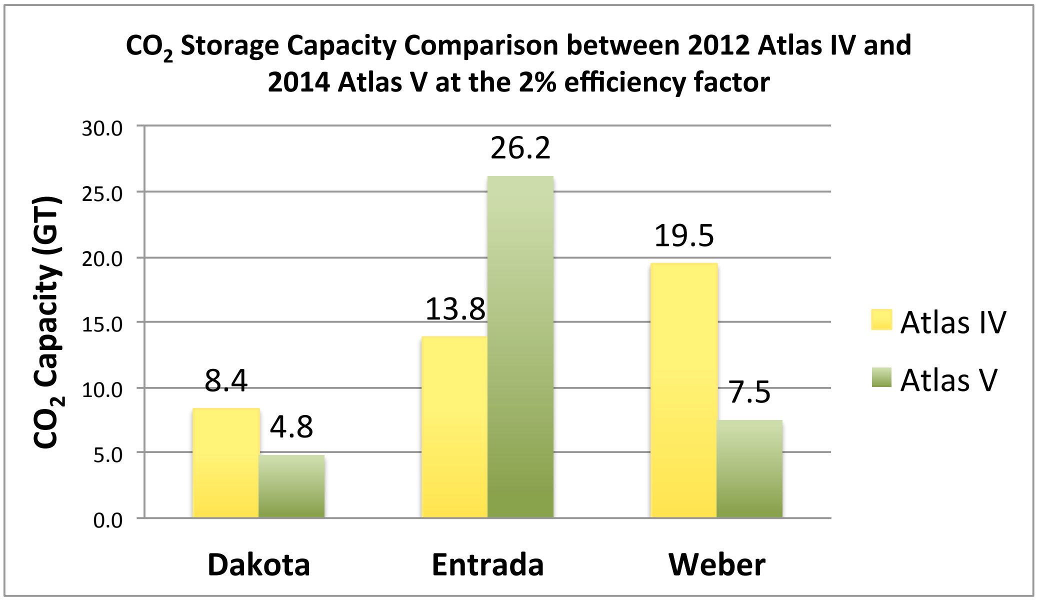
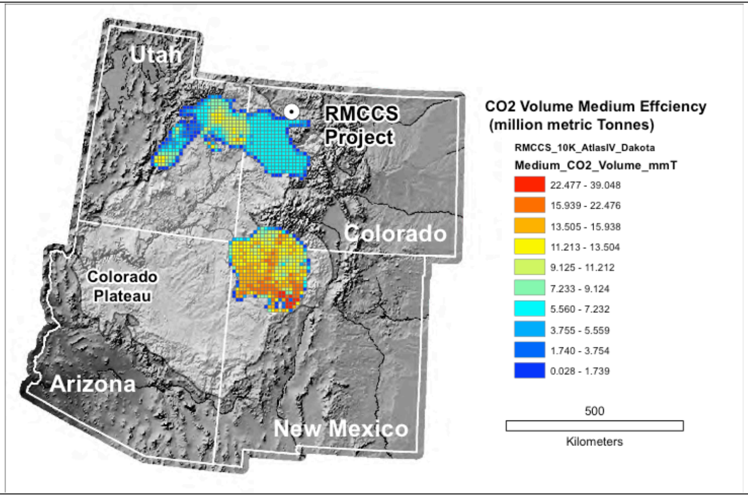
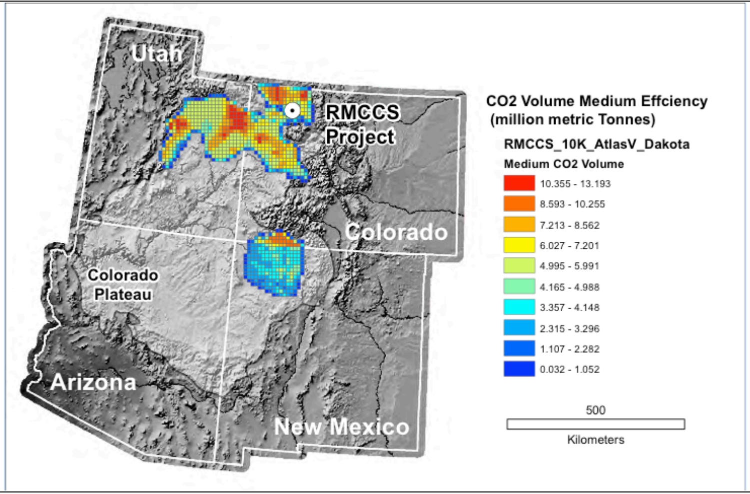
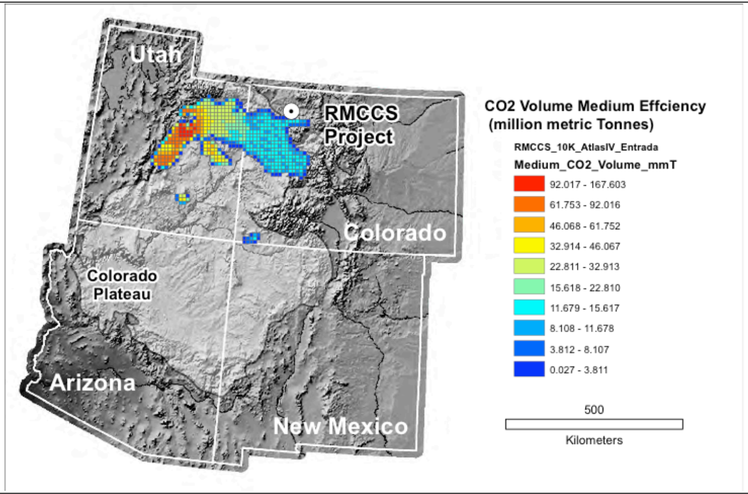
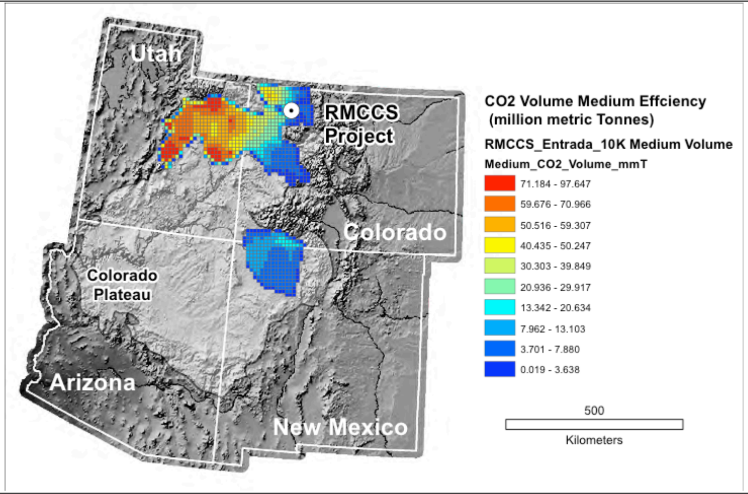


Figure 8: CO_2-storage capacity comparison between Atlas IV and Atlas V data for the three main saline formations on the Colorado Plateau

The spatial differences are shown in Figure 9. The actual numbers in the figures represent the medium capacity volume for each formation. The color ramping is based on the range of the data within each formation and not on a uniform range ramp. Since the low, medium and high volumes are proportional, the color ramp would look the same for the three different efficiency classes within each formation.

The differences in the numbers can be mostly explained by the different areas covered by the two different data sets. The Atlas IV data were derived from interpolated well data that was extracted from the IHS and other public data sources. This project's data are mainly based on expert geological interpretation of the data within the basin. The current New Mexico data are an exception to the expert knowledge interpretation. One of the noticeable differences for the Dakota and the Entrada Formation is the inclusion of the CO Sand Wash Basin (part of the greater Green River Basin) into the updated data. The Entrada is also more extensively mapped in the NM San Juan basin.

	NATCARB Atlas IV	RMCCS project (Atlas V)
Dakota		

	NATCARB Atlas IV	RMCCS project (Atlas V)
Entrada		

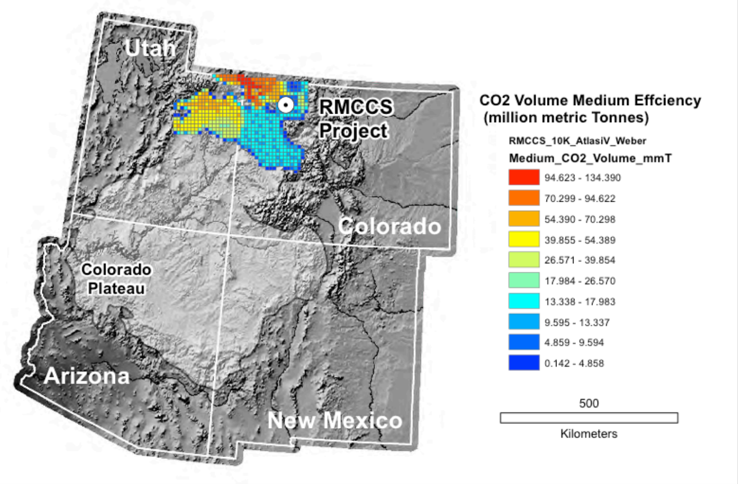
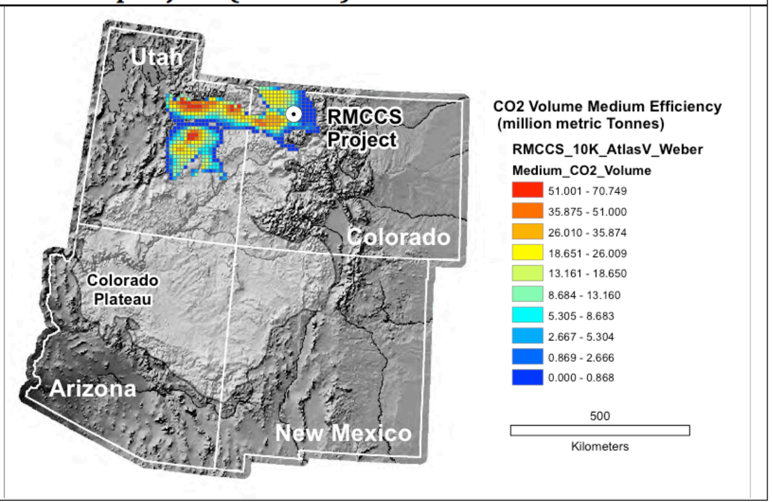
	NATCARB Atlas IV	RMCCS project (Atlas V)
Weber		

Figure 9: Spatial comparison of the CO_2-medium-efficiency-capacity volume between NATCARB Atlas IV (2012) and this project's three major, regional saline aquifer data (in preparation of Atlas V 2014) at the 10 km^2 scale.

The CO_2-storage-capacity numbers determined in this study for the Dakota, Entrada and Weber Formations in the Colorado Plateau for the State of Colorado compare less favorably to the numbers listed by Young et al. (2007). The previous study listed a number of 90 billion metric tonnes at the 2% efficiency while the current numbers tallied up to 10.3 billion metric tonnes.

6. Significance of Regional Capacity Results

The storage capacity results of this analysis are of reasonable, robust quality, and even a qualitative analysis suggests that the estimated capacities are very significant if the results are compared to past estimates (Section 5 of this report), and if compared to other regions of the USA. Perhaps most significant about the estimated regional capacities is not the values in tons, but rather as expressed as number of years of emissions.

Significance of Regional Capacity Estimates in Context of Previous Estimates

As discussed in Section 5 of this report, the newest capacity data reported here are markedly different (Table 8). As outlined in Section 5, the primary explanation for the contrast in results include more data, better quality data, and more-robust geological analysis of those data. Because the data and interpretations are better, the regional capacity estimates may be considered to be more significant in the context of reliability and usefulness. The upshot is that regional capacity estimates will be better and more significant as more resources are invested in the analysis.

Significance of Regional Capacity Estimates in Context of Years of Emissions

Given very recent (late 2013) announcements regarding how existing coal-fired power plants and gas-fired power plants will be regulated, it will be useful to cast the capacity estimates as number of years of emissions, in addition to gross tons. Specifically, according to September, 2013 announcements by the U.S. Environmental Protection Agency, the intent of the federal government is to not require existing plants to implement CCS, but rather only new coal-fired power plants will be required to implement CCS to meet emission reduction goals. Thus, if these rules are approved, the currently operating power plants will continue emissions at their current levels, and most new power plants will likely be gas-fired. Because existing plants will not be subject to retrofit, CO_2 emissions from these point sources will not see a rapid and marked decrease any time in the coming decades. As such, what is the regional capacity of the regional Dakota, Entrada and Weber formations in number of years of current emission rates?

The current total CO_2 emission rate for the combined set of coal-fired and gas-fired power plants in the region is roughly 320 million tons per year, according to a selected subset of rocky mountain emissions data (per NATCARB and its online database accessible at http://www.natcarbviewer.com/). The total storage capacity for the combined Dakota, Entrada and Weber formations is 38,505 million tons (Table 8, medium efficiency factor), translating to approximately 120 years of storage capacity. Over 120 years, it is very likely that emissions rates will not increase (per discussion immediately above), but rather should decline somewhat. Thus, it is not inappropriate to suggest that the regional capacity of these three formations will likely exceed 150 years or more.

Significance of Regional Capacity Estimates as Compared to Eastern USA

With respect to electricity generation, the Rocky Mountain region is dominated by coal. As such, we suggest that the most appropriate comparison of capacity estimates might be to another coal-dominated region of the USA. According to Atlas IV (NETL, 2012), the dominant CO_2 emissions sources in Pennsylvania and surrounding states are electricity generation plants, and these plants are predominantly coal-fired.

For comparison of the Rocky Mountain regional capacity estimates to another coal-dominated region, we selected the region studied by the Midwest Regional Carbon Sequestration Partnership, or MRCSP (http://addap.tk). Data provided by Atlas IV (NETL, 2012) indicates that the total storage capacity of the MRCSP region is approximately 130, 447 million tonnes (143,793 Mtons), almost four times that of the Rocky Mountain regional capacity of the Dakota, Entrada and Weber formations. And, annual CO_2 emissions for the entire region are approximately 670 million tonnes (739 million tons), over twice that of the Rocky Mountain region. However the storage capacity expressed in years for the MRCSP region is not too much more than that of the Rocky Mountain region: approximately 195 years. While this is 75 more years than the Rocky Mountain region, the MRCSP capacity assessment corresponds to no fewer than 13 formations (Waste Gate Fm., Sylvania Fm., Bass Islands Fm., Dundee Fm., Oriskany Fm., Lockport Fm., Medina/Tuscarora Fm., St. Peter Fm., Rose Run Fm., Potsdam Fm., Conasauga Fm., Rome Trough Fm. , and the Mt. Simon Fm.), compared to the Rocky Mountain Region analysis of just the three most promising formations, the Dakota Fm., the Entrada Fm., and the Weber Fm.

7. Conclusions

The derived, CO_2-capacity-storage numbers that were based on solid, geological-based, decision making; combined with available well data; were different from the numbers based on computer generated interpolations from well data only. Having input from geologists that incorporated the structure, basin, and geological discontinuities; resulted in a more realistic interpretation of the data. A computer-interpolation algorithm is not capable of such interpretation. Although it is likely that the current interpretation of the data is better than the method used in Atlas IV (data interpolation only); it is difficult to conclude this objectively without being able to test the results.

The CO_2 storage capacity numbers for the three regional, saline formations reflect a decrease of nearly 8% compared to earlier reported numbers. There are additional refinements that can be made to the input data (porosity and geothermal gradient) for the current methodology, including better structural information such as structural dip or incorporating a better representation of the sedimentary basin structure especially for the San Juan Basin. Improving this general type of information will still not be a substitute for detailed basin models based on calibrated data such as wells, seismic lines and petrophysical logs as were used for this project's model Sand Wash Basin detailed local analysis. Having an indication about data uncertainty would be beneficial to the current methodology as well.

The methodology to calculate the CO_2 storage capacities could be simplified by automating the procedure currently applied within the spreadsheet. This would involve converting the method to an arc python script. Although it would simplify and automate the workflow, it also creates a "black box push button method." We caution use of such an algorithm, inasmuch as it became clear during the data compilation and integration process that most individuals may not fully understand the method unless they actually conduct it step by step. A major disadvantage of using an automated script for the CO_2 capacity calculations is its inflexibility in handling modifications to variable input parameters such as the geothermal gradient.

8. References

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Appendix 1

NATCARB CO_2 sequestration atlas projection parameters:

Projection: Lambert_Azimuthal_Equal_Area
False_Easting: 0.000000
False_Northing: 0.000000
Central_Meridian: -100.000000
Latitude_Of_Origin: 45.000000
Linear Unit: Meter (1.000000)

Geographic Coordinate System: GCS_WGS_1984
Angular Unit: Degree (0.0174532925199433299)
Prime Meridian: Greenwich (0.000000000000000000)
Datum: D_WGS_1984
  Spheroid: WGS_1984
    Semimajor Axis: 6378137.000000000000000000
    Semiminor Axis: 6356752.314245179300000000
    Inverse Flattening: 298.257223563000030000

Appendix 2

NATCARB Carbon Sequestration Atlas Saline formations database template data dictionary:

SALINE

FIELD	ALIAS	DATA_TYPE	WIDTH	UNITS	DOMAIN?	DESCRIPTION
PARTNERSHI	PARTNERSHI	Text	15		Yes	Abbreviated partnership name
RESOURE_N	RESOURE_N	Text	50			Name of storage resource
ASSESSED	ASSESSED	Short Integer			Yes	1 = Yes, storage resource has been assessed.; 0 = No, storage resource has not been assessed.

SALINE10K

FIELD	ALIAS	DATA_TYPE	WIDTH	UNITS	DOMAIN?	DESCRIPTION
COL_ROW	COL_ROW	String	20			10K unique ID
PARTNERSHI	PARTNERSHI	Text	15		Yes	Abbreviated partnership name
RESOURE_N	RESOURE_N	Text	50			Name of storage resource
RSC_AREA_C	RSC_AREA_C	Double		sq. m.		Area of the storage resource within the cell in square meters
VOL_LOW*	VOL_LOW	Double		tonnes		Low (P10) storage resource estimate in metric tonnes per cell. Value must be <null> if Assessed = 0
VOL_MED*	VOL_MED	Double		tonnes		Medium (P50) storage resource estimate in metric tonnes per cell. Value must be <null> if Assessed = 0
VOL_HIGH*	VOL_HIGH	Double		tonnes		High (P90) storage resource estimate in metric tonnes per cell. Value must be <null> if Assessed = 0
DEPTH_FT**	DEPTH	Long Integer		feet		Mean depth to top (from surface) of storage resource per cell to the nearest 5' increment
THICKNESS_	THICKNESS	Long Integer		feet		Mean thickness of storage resource per cell to the nearest 5' increment
SALINITY_TD	SALINITY	Long Integer		ppm		Mean salinity (TDS) of storage resource per cell in ppm to the nearest whole number
PRESSURE_P	PRESSURE	Short Integer		PSI		Mean pressure at top of storage resource per cell in PSI to the nearest whole number
TEMPERATU	TEMPERATU	Short Integer		degrees F		Mean temperature at top of storage resource per cell in degrees F to the nearest whole number
POROSITY_P	POROSITY	Float		percent		Mean porosity of storage resource per cell in percent to the nearest tenth
PERMEABILIT	PERMEABILIT	Float		mD		Mean permeability of storage resource per cell in millidarcies
ASSESSED	ASSESSED	Short Integer			Yes	1 = Yes, storage resource has been assessed. Storage estimates may be zero; 0 = No, storage resource has not been assessed. Storage estimates must be null.
ARRA_PROJECT		Text	20			

* Field is defined as a DOUBLE in order to accept large numbers, but values should be rounded to nearest whole number.

** Value applies to the "storage zone" portion of the storage resource