SIMULATION OF CO_2 STORAGE IN THE BASAL AQUIFER IN THE NORTHERN PLAINS–PRAIRIE REGION OF NORTH AMERICA

Dorothee Rebscher, Quanlin Zhou, and Jens T. Birkholzer

Lawrence Berkeley National Laboratory
Earth Sciences Division 90-1116
Berkeley, CA, 94720, USA
e-mail: drebscher@lbl.gov

ABSTRACT

The static storage capacity in the Basal Aquifer in the Northern Plains–Prairie Region of North America has been estimated to be more than 10^5 GT (billion metric tonnes) CO_2. This large capacity can be attributed to: (1) the aquifer's area of ~1,500,000 km^2 covering the Alberta Basin and the Williston Basin in Alberta, Saskatchewan, and Manitoba in Canada, and Montana, North Dakota, and South Dakota in the U.S.; and (2) a porosity range from 1% to 25%, a permeability range from 10 to 10^3 mD, and an aquifer thickness up to 300 m. However, the static storage capacity does not consider the effect of pressure buildup induced by CO_2 injection, by which overpressurization might fracture the cap rock, drive brine/CO_2 leakage, and cause induced seismicity. During storage operation, pressure buildup will be controlled under maximum injection pressure to avoid the above negative impacts, leading to a more realistic, dynamic storage capacity. That capacity can be estimated through numerical modeling of CO_2 injection and storage.

We have developed a TOUGH2-MP/ECO2N model for the Basal Aquifer to simulate pressure buildup and dynamic storage capacity, as well as the distribution, migration, and long-term fate of CO_2 plumes in response to CO_2 injection at multiple storage sites. This model development is based on a detailed geologic model, as well as hydrogeological properties and their spatial distributions, and the *in situ* conditions of pressure, temperature and salinity—all of which were provided by our partners. Eleven storage sites, with a cluster of injection wells for each one, are selected through the mapping between CO_2 emissions and sinks (for storage) for the Canadian portion of the aquifer. The number of injection wells at each site is determined using screening modeling, with special attention to pressure buildup. We generated an unstructured 3D grid using WinGridder to account for local 3D mesh refinement around each storage site to capture the evolution of CO_2 plumes, and also generated a single reservoir model layer out of CO_2 plumes to capture the single-phase pressure propagation. The current TOUGH2 model covers the Basal Aquifer, the cap rock, and the basement rock, without consideration of CO_2/brine leakage through abandoned wells. Simulation results indicate that (1) the dynamic storage capacity of the extensive saline aquifer is smaller than the estimated static storage capacity because of localized pressure-buildup constraints, and (2) the degree of the constraints varies over the entire aquifer as a result of (i) the large range in permeability, (ii) the pressure interference between different storage sites and injection wells, and (iii) the realistic CO_2 source-sink mapping for locating and designing storage sites.

INTRODUCTION

The Northern Plains–Prairie Basal Aquifer System is considered an important potential site for the sequestration of carbon dioxide in geological media (e.g., Bachu and Stewart, 2002). The saline aquifer extends over about 1,500,000 km^2 in the southwestern Canadian states and northern prairie states on the U.S. side. This paper focuses on the Canadian portion of the Basal Aquifer in Alberta, Saskatchewan, and Manitoba, covering 811,000 km^2. The model area is marked by the thin white line in the Google map in Fig. 1. Also shown are the locations of the CO_2 injection sites, indicated by red dots. Numerical modeling of the Basal Aquifer over its huge areal extent poses a great challenge, in comparison to other smaller sedimentary basins targeted for potential storage. In such efforts, both high-resolution modeling of the CO_2 plume around each injection well and low-resolution modeling of the pressure buildup out of the CO_2 plumes at the basin scale are required for reasonable modeling accuracy. A comparable study on basin- and plume-scale modeling of CO_2 sequestration was conducted for the Illinois Basin by Birkholzer and Zhou (2009) and Zhou et al. (2010).

BACKGROUND

All the data for aquifer characterization, including aquifer geometry, rock properties (porosity, permeability, and pore compressibility), capillary pressure, and relative permeability, were provided by our project partner Alberta Innovates–Technology Futures (AITF) (Bachu et al., 2012).

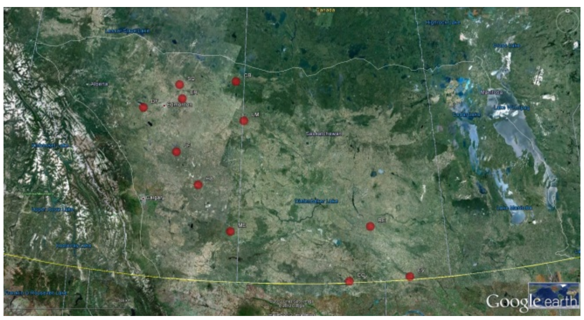

Figure 1. The areal extent (811,000 km^2) of the Basal Aquifer in Alberta, Saskatchewan, and Manitoba in Canada, with its boundary marked by a thin white line and a yellow border line. Eleven storage sites are marked by red dots.

Geology

The Basal Aquifer covers part of the Alberta Basin and the Williston Basin. It consists of several distinctive stratigraphic units: (1) the Basal Cambrian Sandstone unit, (2) a combination of the Basal Cambrian Sandstone unit and Black Island Member of the Winnipeg Formation, (3) the Black Island Member of the Winnipeg Formation, and (4) a combination of the Black Island Member and the Icebox Member of the Winnipeg Formation, which are in hydraulic communication. Its vertical upper border is mainly defined through the first significant overlying cap rock. The Basal Aquifer varies significantly in depth, reaching 5 km near the Rocky Mountains in the west and cropping out towards the east, where the environmental impact of CO_2 storage on freshwater resources may be a concern (Bachu et al., 2012).

Hydrogeological Parameters

Within the Basal Aquifer, hydrogeological properties vary significantly in the vertical and horizontal directions. Porosities range from 1% to 25%, and permeabilities from about 10 mD to 10^3 mD. For example, Table 1 shows the representative values of porosity and permeability at the 11 storage sites. The maximum thickness of the saline aquifer usable for CO_2 sequestration is 300 m.

CO_2 Injection Scenario

The area of interest comprises a significant number of large stationary CO_2 sources, whose total CO_2 emissions amounts to more than 10% of Canada's total greenhouse gas emissions. Eleven storage sites were chosen by AITF on the Canadian side with different amounts of CO_2 to be stored. Their emission ranges from 1.2 to 23 Mt CO_2/year, summing up to a total of 75.1 Mt CO_2/year (see Table 1), corresponding to 86% of the total emissions of large point sources, with more than 1 Mt CO_2/year in the area. Due to the high amount of CO_2 emissions at some of the sites, we determined well arrays, where each well is considered to sequester about 1.5 Mt CO_2 per year, leading to 50 boreholes for the entire saline aquifer in Canada.

Table 1. The 11 injection sites in Alberta and Saskatchewan and their amount of CO_2 to be sequestered and their hydrogeological properties, (from AITF and Geological Survey of Saskatchewan.)

location	CO_2 Mt/y	no. of wells	depth [m]	thickness [m]	porosity [%]	permeability [mD]
Cold Lake - Bonnyville, AB	8.3	6	1259	80	18	1000
Shell Quest Radway, AB	1.2	1	2013	42	14.5	500
Edmonton - Redwater, AB	9.7	6	2055	77	13	500
Duffield, AB	23	15	2964	36	7	100
Lloydminster, SK	2.1	1	1578	109	22	500
Joffre - Forestburg AB	7.1	5	2673	67	7.5	35
Hanna, AB	4.4	3	2427	48	10	50
Regina, SK	1.7	1	2235	48	14	1000
Medicine Hat - Empress, AB	5.2	3	2010	142	8	750
Estevan, SK	8.6	6	2719	59	6	50
Coronach, SK	3.8	3	2667	75	5.5	50
total	75.1	50	-	-	-	-

SCREENING MODELING WITH ANALYTICAL SOLUTION

For the CO_2 source-sink mapping, we used a four-layer model, with alternating aquifers/aquitards for each of the 11 storage sites listed in Table 1. The subsurface systems consist of a top aquifer, the cap rock, the Basal Aquifer, and the Precambrian basement, which were assumed to be homogeneous and isotropic in the horizontal direction. The hydrogeological parameters were derived from the extensive confidential dataset provided by AITF. Model input parameters (layer thickness, hydraulic conductivity, specific storativity) were calculated. Injection rates and number of wells are listed in Table 1. The locations of the storage sites and the spatial distribution of injection wells at each site are kept unchanged for both the screening modeling and the TOUGH2 simulations. The pressure buildup in the four layer systems were calculated using the analytical solution (Cihan et al., 2011). Injection of an equivalent volume of brine was simulated as the single-phase model is accurate in the far-field away from the CO_2 plumes. The injection period is 50 years.

Figure 2 shows the pressure buildup at the end of the 50-year injection at the Regina site with one injection well. The injection of equivalent volume is 4,257 m^3/d and the permeability 1,000 mD, leading to a maximum pressure buildup of 7.5 bar at a radius of 250 m from the injection well at 50 years. Figure 3 shows the pressure buildup at the Duffield site with 15 wells at 5 different time steps as examples. The spatial distribution of the pressure buildup for these two sites is illustrated in Figures 4 and 5, respectively. They show that Regina might not be an issue because of the high permeability there—see Table 1.

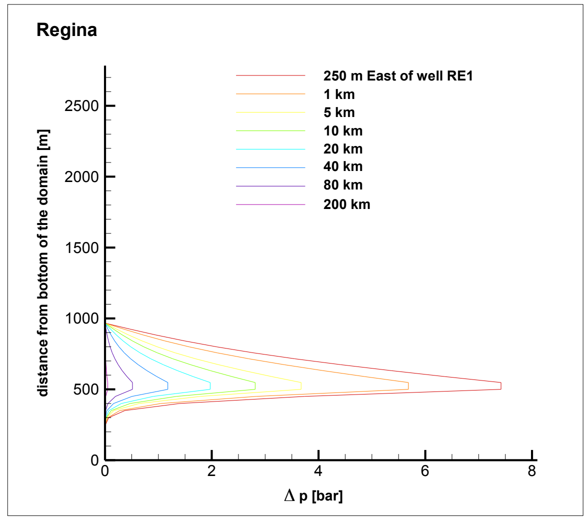

Figure 2. Pressure buildup in the top aquifer, the cap rock, the Basal Aquifer, and Precambrian basement at different radial distances after the injection of equivalent volume of 4,257 m^3 /d for 50 years at the Regina site

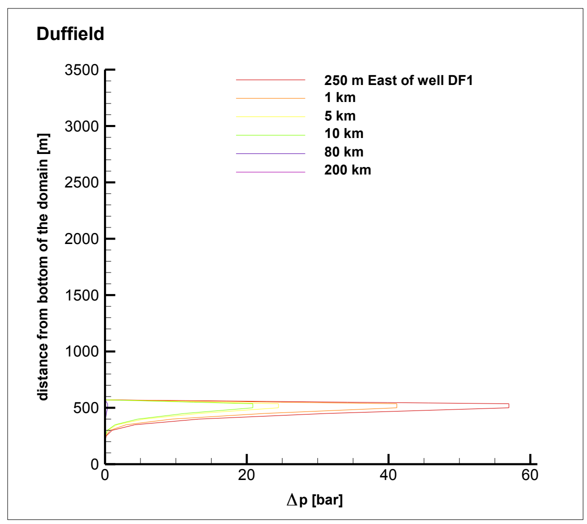

Figure 3. Pressure buildup in the top aquifer, the cap rock, the Basal Aquifer, and the Precambrian basement at different horizontal distances along the easting after the injection of equivalent volume of 3,617 m^3/d for 50 years at the Duffield site

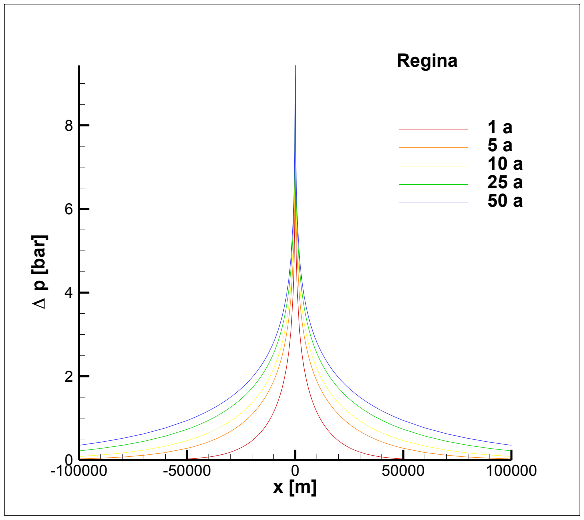

Figure 4. Pressure buildup in the Basal Aquifer at different times during the injection period at the Regina site. The cross section is located at the Easting-axis.

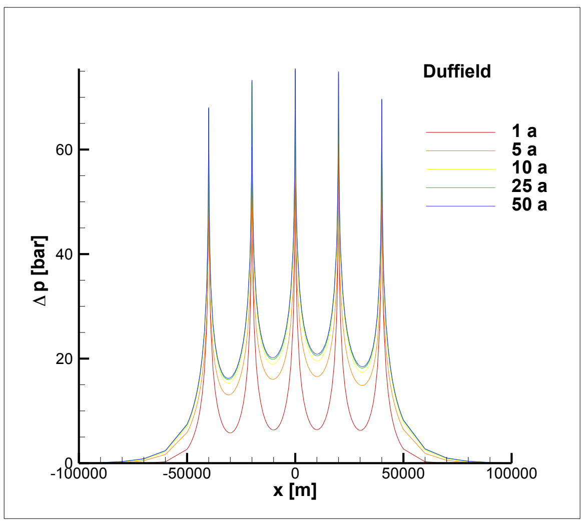

Figure 5. Pressure buildup in the Basal Aquifer at different times during the injection of 4257 m^3 CO_2/d into each of 15 wells for 50 years at the Duffield site. The cross section goes through the five wells located on the easting-axis, centered around DF1, see Figure 7.

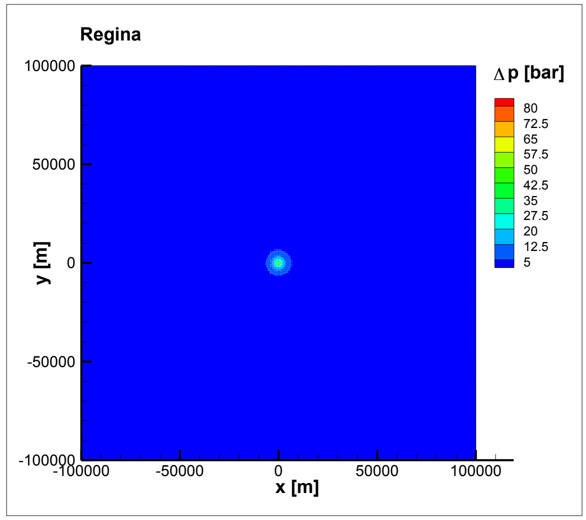

Figure 6. The spatial distribution of the pressure buildup in the Basal Aquifer at the Regina site.

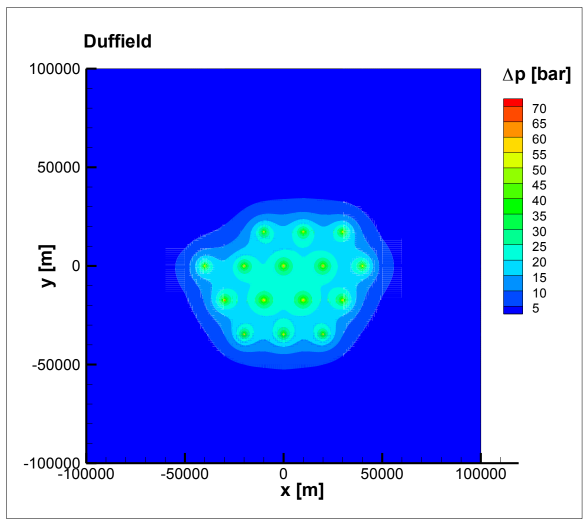

Figure 7. The spatial distribution of the pressure buildup in the Basal Aquifer at the Duffield site.

TOUGH2 MODEL DEVELOPMENT

Map Projection

To develop the basin-scale numerical model, we determined the model domain based on the dataset provided by AITF for the Canadian side of the Basal Aquifer Region. The modified Universal Transverse Mercator (UTM) projection was used as a map projection, consistent with the projection used by Princeton University for model comparison. The coordinates for the entire model domain were calculated using the reference of the -111°

meridian, the central meridian for UTM zone 12, the zone for East Alberta and West Saskatchewan, where many injection clusters are located. The error in area is less than 1% for a neighboring UTM zone, and less than 2% for other relevant UTM zones.

The Unstructured 2D Mesh

The well locations are arranged along a hexagonal spiral, were the center represents the actual site of the emission centers (see Table 1), starting in the spiral center with no. 1, clockwise ascending. An exception was made for the two most-southern sites in Saskatchewan, Estevan and Coronach, as otherwise some of the boreholes would have been situated in the U.S., outside of the domain boundary. Their centers were shifted 40 km to the north. In order to minimize interference between neighboring injection sites (the minimal areal distance between two injection centers is 42 km, equal to that between SQ and ER). Given the expense in pipeline infrastructure on the one hand and the need to minimize interference from CO_2 plumes within one array on the other, we chose a distance of 20 km between wells within one array.

A numerical grid was generated for our basin-scale model. Different grid resolutions were used over the entire domain (see Figs. 8 through 11). For each cluster, a 200 km×200 km subdomain centered at the cluster center was used with a mesh resolution of 10 km×10 km. For these cluster subdomains, we used a mesh resolution of 20 km×20 km. Within these subdomains, a 100 km × 100 km near-field region was defined, with a resolution of 3 km×3 km. Within each near-field, the well locations were arranged along a hexagonal spiral, with the center representing the actual cluster center, starting in the spiral center with number 1, then clockwise ascending. To resolve the time-dependent evolution of the CO_2 plume, we used an unstructured 2D subgrid for each injection well, with a progressive decrease in mesh resolution away from the injection well. Thirty-two concentric circular rings (with 16 nodes for each ring) were used to cover the CO_2 plume; the radial discretization ranged from 50 m to 500 m, with a total radius of 7 km for each plume. A total of 36,000 2D grids were generated using WinGridder (Pan et al., 2001). In the vertical direction, the Basal Aquifer (with a maximum thickness of 400 m) was divided into 25 model layers, covering a thickness of 50 m to 150 m at the injection clusters. The minimum thickness of the model layers was 1 m. For the near field, four model layers were used for the subdomains, with a mesh resolution of 10 km×10 km, while only one model layer was used for the regions with a mesh resolution of 20 km×20 km. In these coarsened-mesh regions, only pressure buildup is of interest to simulations, and pressure buildup in response to CO_2 injection equilibrates quickly in the vertical direction. The generated 3D mesh consists of ~750,000 gridblocks for the entire Canadian part of the Basal Aquifer.

In this model, it is assumed that the difference between hydrogeological parameters of the Basal Aquifer, compared to those of the cap rock and underlying aquitard, is sufficient for CO_2 leakage into or through the aquitards to be neglected. In the vertical direction, the hydrogeological layer of the Basal Aquifer was divided into 25 model layers, covering the thickness of the Basal Aquifer to a maximum of 400 m within the domain, but having a thickness of only 50 m to 150 m at the injection sites. The minimum thickness of the model layers was 1 m.

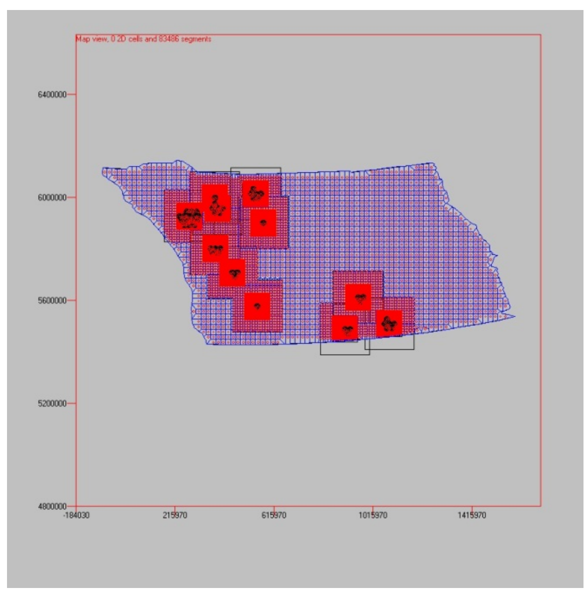

Figure 8. The model domain is subdivided into several grids with varying resolutions.

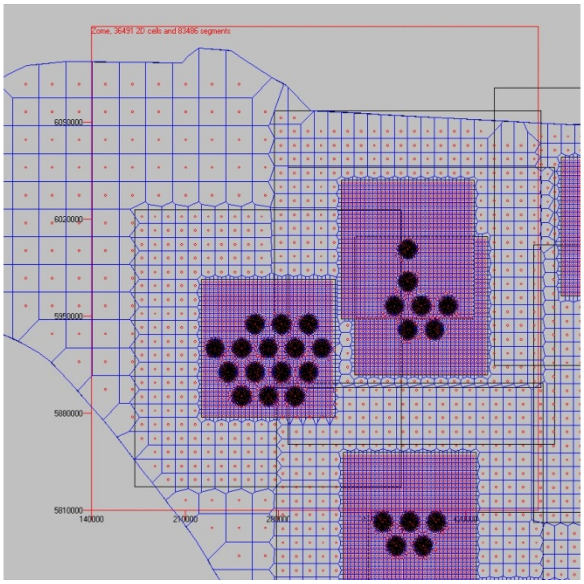

Figure 9. Square plan form gridblocks with sides of 200 km have the next highest resolution with 10 km x 10 km. This excerpt shows the North western part of the domain with the clusters Shell Quest (1 well, in the North), Duffield (15 wells, in the West), Edmonton - Redwater (6 wells, south of Shell Quest), and Joffe (5 wells, in the South).

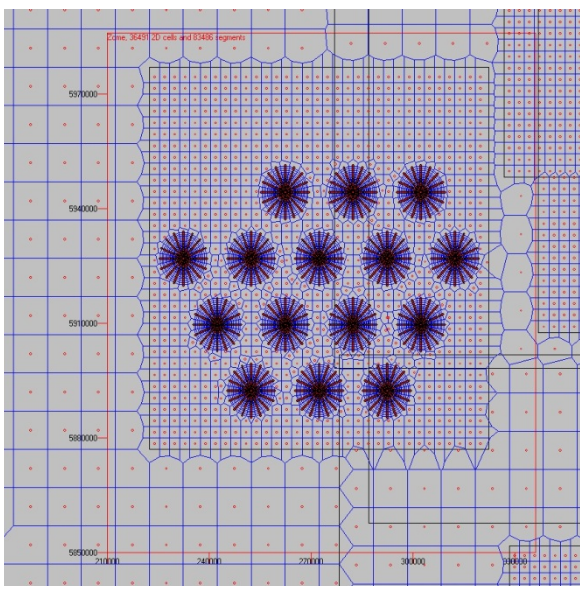

Figure 10. The wells are surrounded by a rectangular grid with sides of 100 km and resolutions of 3 km x 3 km. The Duffield array with 15 wells has the highest number of boreholes.

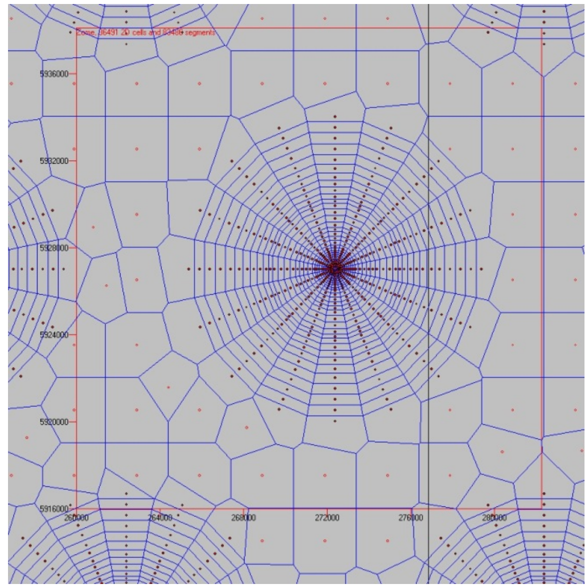

Figure 11. Each well consists of 32 concentric rings with radii from 50 m to 7 km, each formed by 32 points - here the central well in the Duffield borehole array DF1.

SIMULATION

Total annual injection rate is 75.1 Mt CO_2 (Bachu, 2012) over 50 years, distributed to 50 injection wells at 11 injection sites independent of the local emissions of CO_2; see Table 1. Calculations will be performed using the general-purpose numerical simulation program TOUGH2 (Pruess et al., 1999), with the equation of state module ECO2N (Pruess, 2005).

RESULTS AND DISCUSSION

Discussion of the simulations at the Symposium will emphasize basin and plume scale results. The time-dependent development of the CO_2 plume will be analyzed. One focus will be on pressure buildup, which governs the cap-rock integrity. Last but not least, special attention will be given to the dynamic storage capacity.

SUMMARY AND CONCLUSION

Combining the fact that prominent stationary CO_2 emitters are distributed unevenly over the area of interest—with varying spatial distributions of porosity, permeability, and aquifer thickness—the predictive simulations show large regional differences in the dynamic storage capacity of this extensive saline system.

FUTURE WORK

Key future activities include: (1) extending the domain to the south, i.e., including the U.S. part (in North Dakota and Montana) of the aquifer, based on data that will be provided by the Energy & Environmental Research Center (EERC), University of North Dakota; (2) comparison with simulations currently under way by Princeton University.

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