Training Students in Simulation & Risk Assessment for Carbon Sequestration

DE-FE0002059

John McCray
Department of Civil and Environmental Engineering

U.S. Department of Energy
National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO₂ Storage
August 20-22, 2013
Presentation Outline

- Benefits to Program
- Project Overview: Goals, objectives, tasks
- Accomplishments
- Technical Status and Findings
- Summary: Lessons Learned & Future Work
- Bibliography
Benefit to the Program

Program goals being addressed.

- Develop technologies that will support industries’ ability to predict CO₂ storage capacity in geologic formations to within ±30 percent.

From the RFP: “… provide training opportunities for graduate and undergraduate students that will provide the human capital and skills required for implementing and deploying CCS technologies. Training can be accomplished through fundamental research ….

Fundamental research is needed to advance science in: simulation and risk assessment; …. verification, and accounting; …. and integrity for long-term CO₂ storage and capture.
Benefit to the Program

Benefits are related to both training and research.

Training:

• Train advanced professionals to enter the CCS field

Research:

• Enhance public confidence in sequestration (maintain license to operate and reduce costs)
• Reduce environmental footprint
The primary objectives of the project are to *train students* and *advance the science* in two critical areas of risk assessment:

1. multi-process, multi-scale model simulation: risks associated with leakage into overlying aquifers;
2. pore-scale geochemical processes in CO$_2$ sequestration needed to assess the environmental impact and the likelihood of a successful sequestration effort.
Project Overview: Goals and Objectives

Success criteria:

– MS students complete thesis & receive graduate degrees
– PhD student completes dissertation, & receives PhD degree.
– Post-doctoral researcher achieves career position
– Simulations and experiments are completed.
– 5 peer-reviewed journal articles are submitted/accepted (goal: 1 per MS student and 3 per PhD student)
Accomplishments to Date

- Alexis Sitchler (PhD Penn State) has received training as a project manager for this project, and recently agreed to a tenure-track faculty position in the Geology & Geological engineering Dept at CSM. She will continue a career in GCS research.

- Erica Siirilla (B.S. Univ. Colorado) completed PhD degree in May 2013. Moving to Post-doc position in Spain.

- Hannah Menke (B.S. Columbia Univ) completed her M.S. degree (Environmental Engineering). Currently in PhD program in CCS at Imperial College (London).

- Katy Kirsch (BS Middlebury College) completed M.S. Thesis (Hydrology) in May.
Accomplishments to Date

- Developed and delivered (twice) a graduate-level course on carbon sequestration, focusing on fundamental applied concepts and papers from the literature. More than 35 graduate students received training via course.

- 2 M.S. Theses completed (Siirilla and Menke)

- 5 peer-reviewed papers completed.

- Risk assessment methodology created.

- Experimental protocol developed, experiments complete
Technical Status

Because this is a training grant, we have arranged this section by student:

- Erica Siirilla
- Hanna Menke
- Katie Kirsch

- Will focus on the work of Katy Kirsch (presented other work last year)
Overview: Development of a Quantitative Human Health Risk Framework for CO₂ Leakage

A: CO₂ leakage and dissolution of metals

B: Heterogeneous flow and transport of metals

C: Possible capture in one or more down-gradient wells

D: Water delivery system to many different households

E: Household exposure and health risk via multiple pathways to varying individuals
A quantitative methodology to assess the risks to human health from CO₂ leakage into groundwater

Erica R. Siirila a,c,*, Alexis K. Navarre-Sitchler b, Reed M. Maxwell a,c, John E. McCray b,c

a Department of Geology and Geological Engineering, Colorado School of Mines, Golden, CO 80401, United States
b Environmental Science and Engineering Division, Colorado School of Mines, Golden, CO 80401, United States
c Hydrologic Science and Engineering Program, Colorado School of Mines, Golden, CO 80401, United States

ABSTRACT

Leakage of CO₂ and associated gases into overlying aquifers as a result of geologic carbon capture and sequestration may have adverse impacts on aquifer drinking-water quality. Gas or aqueous-phase leakage may occur due to transport via faults and fractures, through faulty well bores, or through leaky confining materials. Contaminants of concern include aqueous salts and dissolved solids, gaseous or aqueous-phase organic contaminants, and acidic gas or aqueous-phase fluids that can liberate metals from aquifer minerals. Here we present a quantitative risk assessment framework to predict potential human health risk from CO₂ leakage into drinking water aquifers. This framework incorporates the potential release of CO₂ into the drinking water aquifer; mobilization of metals due to a decrease in pH; transport of these metals down gradient to municipal receptors; distributions of contaminated groundwater to multiple households; and exposure and health risk to individuals using this water for household purposes. Additionally, this framework is stochastic, incorporates detailed variations in geological and geostatistical parameters and discriminates between uncertain and variable parameters using a two-stage, or nested, Monte Carlo approach. This approach is demonstrated using example simulations with hypothetical, yet realistic, aquifer characteristics and leakage scenarios. These example simulations show a greater risk for arsenic than for lead for both cancer and non-cancer endpoints, an unexpected finding. Higher background groundwater gradients also yield higher risk. The overall risk and the associated uncertainty are sensitive to the extent of aquifer stratification and the degree of local-scale dispersion. These results all highlight the importance of hydrologic modeling in risk assessment. A linear relationship between carcinogenic and noncarcinogenic risk was found for arsenic and suggests action levels for carcinogenic risk will be exceeded in exposure situations before noncarcinogenic action levels, a reflection of the ratio of cancer and non-cancer toxicity values. Finally, implications for ranking aquifer vulnerability due to geologic configuration, aquifer mineralogy, and leakage scenarios are discussed.

© 2010 Elsevier Ltd. All rights reserved.
Drawing Connections Between Geochemical Reactions and Aquifer Transport at Different Scales

(A) At the leakage source: aquifer:

- Multi-component, nonlinear geochemical reactions and fluid transport
- Run until a steady-state metal concentration and pH are achieved

(B) Far-field

- Steady-state concentration from (A) used as initial metal concentration
- Contaminant plume modeled with a particle-tracking technique
- Linear reactions
Includes a Robust, Probabilistic Treatment of Risk: The Nested Monte Carlo Approach

Outer, Uncertainty Loop

Inner, Variability Loop
Yields Risk as a Function of Uncertainty and Variability

Example simulations show:

1. The specific metal mobilized in the event of CO$_2$ leakage greatly affects the outcome of risk

1. Hydrologic aquifer properties such as the degree of stratification and local dispersion greatly affect the magnitude and distribution (i.e. uncertainty) of risk

1. Risk is sensitive to the hydrologic flow parameters and warrants further examination in CCS risk assessment
Evaluating effective reaction rates of kinetically driven solutes in large-scale, statistically anisotropic media: Human health risk implications

Erica R. Siirila¹,² and Reed M. Maxwell¹,²,³

Received 17 October 2011; revised 20 January 2012; accepted 7 March 2012; published 25 April 2012.

The interplay between regions of high and low hydraulic conductivity, degree of aquifer stratification, and rate-dependent geochemical reactions in heterogeneous flow fields is investigated, focusing on impacts of kinetic sorption and local dispersion on plume retardation and channeling. Human health risk is used as an endpoint for comparison via a nested Monte Carlo scheme, explicitly considering joint uncertainty and variability. Kinetic sorption is simulated with finely resolved, large-scale domains to identify hydrogeologic conditions where reactions are either rate limited (nonreactive), in equilibrium (linear equilibrium assumption is appropriate), or are sensitive to time-dependent kinetic reactions. By utilizing stochastic ensembles, effective equilibrium conditions are examined, in addition to parameter interplay. In particular, the effects of preferential flow pathways and solute mixing at the field-scale (macrodistribution) and subgrid (local dispersion, LD) are examined for varying degrees of stratification and regional groundwater velocities (\(v\)). Results show effective reaction rates of kinetic ensembles with the inclusion of LD yield disequilibrium transport, even for averaged (or global) Damköhler numbers associated with equilibrium transport. Solute behavior includes an additive tailing effect, a retarded peak time, and results in an increased cancer risk. The inclusion of LD for nonreactive solutes in highly anisotropic media results in either induced solute retardation or acceleration, a new finding given that LD has previously been shown to affect only the concentration variance. The distribution, magnitude, and associated uncertainty of cancer risk are controlled by the up scaling of these small-scale processes, but are strongly dependent on \(v\) and the source term.

Even when equilibrium conditions were expected based on Da number (i.e. slow groundwater velocities), the effect of kinetic reactions is apparent.

- Faster breakthrough, lower peak concentration, but more tailing
- Higher overall risk

Significant Findings Include:

**Equilibrium Scenario**

**Kinetic Scenario**
A new perspective on human health risk assessment: Development of a time dependent methodology and the effect of varying exposure durations

Erica R. Siirila a, c, *, Reed M. Maxwell a, b, c, 1

a Hydrologic Science and Engineering Program, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, United States
b Integrated Groundwater Modeling Center (IGWMC), Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, United States
c Department of Geology and Geological Engineering, Colorado School of Mines, 1500 Illinois St., Golden, CO 80401, United States

ARTICLE INFO

Article history:
Received 20 March 2012
Received in revised form 9 May 2012
Accepted 9 May 2012
Available online 9 June 2012

Keywords:
Cancer risk
Stochastic
Uncertainty
Variability
Kinetic
Arsenic

ABSTRACT

We present a new Time Dependent Risk Assessment (TDRA) that stochastically considers how joint uncertainty and inter-individual variability (JUV) associated with human health risk change as a function of time. In contrast to traditional, time independent assessments of risk, this new formulation relays information on when the risk occurs, how long the duration of risk is, and how risk changes with time. Because the true exposure duration (ED) is often uncertain in a risk assessment, we also investigate how varying the magnitude of fixed size durations (ranging between 5 and 70 years) of this parameter affects the distribution of risk in both the time independent and dependent methodologies. To illustrate this new formulation and to investigate these mechanisms for sensitivity, an example of arsenic contaminated groundwater is used in conjunction with two scenarios of different environmental concentration signals resulting from rate dependencies in geochemical reactions. Cancer risk is computed and compared using environmental concentration ensembles modeled with sorption as 1) a linear equilibrium assumption (LEA) and 2) first order kinetics (Kin). Results show that the information attained in the new time dependent methodology reveals how the uncertainty in other time-dependent processes in the risk assessment may influence the uncertainty in risk. We also show that individual susceptibility also affects how risk changes in time, information that would otherwise be lost in the traditional, time independent methodology. These results are especially pertinent for forecasting risk in time, and for risk managers who are assessing the uncertainty of risk.

© 2012 Elsevier B.V. All rights reserved.
Traditional: Risk calculated *during this time of contamination*

1. Information on how risk changes as a function of time: \( \frac{d(Risk)}{dt} \)
2. A comparison of risk duration versus magnitude

Overall risk may be higher if we consider a lower exposure over a longer period of time
Understanding Multiphase Fluid Leakage through Fault Zones during Geological Carbon Sequestration Using Numerical Simulations

Paper in preparation for submission to International Journal of Greenhouse Gas Control

Author names and affiliations
H P Menke1* (h.menke12@imperial.ac.uk), A K Navarre-Sitchler1,2 (asitchle@mines.edu), P. Lichtner4 (Peter.Lichtner@gmail.com), G. Hammond5 (glenn.hammond@pnnl.gov), A Wunsch3 (awunsch@mines.edu), R M Maxwell2,3 (rmaxwell@mines.edu), J E McCray1,3 (jmccray@mines.edu),

1 Civil and Environmental Engineering Department, Colorado School of Mines, 1500 Illinois St, Golden, CO, 80401, USA

2 Geology and Geological Engineering Department, Colorado School of Mines, 1500 Illinois St, Golden, CO, 80401, USA

3 Hydrologic Science and Engineering Program, Colorado School of Mines, 1500 Illinois St, Golden, CO, 80401, USA

4 Guest Scientist Los Alamos National Laboratory, Los Alamos NM, USA

4 Pacific Northwest National Laboratory, Richland WA, USA
Menke: Numerical multiphase simulations to investigate leakage through a fault

- Simulations Conducted at Golden Energy Computing Organization (GECO). Run for 3 years of injection, then 0.5 years for pressure/saturation equilibration.

- Variables included: variations in fracture permeability, injection rate, and distance from injection to fracture.

Won the best student presentation at the Front Range Consortium for Research Computing Symposium
Menke: Findings

-Initially (which might be a long time), brine leakage is significantly higher than CO2 leakage on a mass basis. We should pay attention to brine leakage.

-Brine leakage may increase for conditions where CO2 leakage decreases (lower injection pressures, further distance from fault) due to relative permeability considerations.

-Leakage ends more quickly after stopping injection for lower injection rates and shorter injection periods. Suggests pulsed injection might reduce leakage risks.
CO\textsubscript{2}-induced metal release from sandstones: implications for geologic carbon sequestration

Katie Kirsch,\textsuperscript{†,‡} Alexis K. Navarre-Sitchler,\textsuperscript{*,†,‡} Assaf Wunsch,\textsuperscript{†,¶} and John E. McCray\textsuperscript{†,¶}

Hydrologic Science and Engineering Program, Colorado School of Mines, USA, Department of Geology and Geological Engineering, Colorado School of Mines, USA, and Department of Civil and Environmental Engineering, Colorado School of Mines, USA

Submitted to Environmental Science & Technology, July 2013
Kirsch: Dissolution Experiments with Siliclastic Rocks

Investigate the geochemical response of sandstone aquifers to CO$_2$ leakage

Samples were collected from outcrop of the Mesaverde Group in northwestern Colorado.

These sandstones currently yield water to wells for local domestic and agricultural purposes, and have the potential for increased groundwater development in a water-scarce future.
Rock characterization: which minerals are likely controlling the aqueous concentration of metals?

- XRD
- SEM/EDX
- Point count
- Sequential extraction
Experiments: How does the fluid composition and microbiology change with time at elevated CO$_2$ partial pressures?

Pressures up to 1 bar above atmospheric, representative of aquifers, yet small enough to enable cost-effective experimental apparatus.
Dissolution of carbonate minerals in silicate rock can significantly buffer pH

- $pCO_2 = 0.01 \text{ bar}$
- $pCO_2 = 1.0 \text{ bar}$

*Time (days)*

*Scale bar: 100 μm*
CO₂-acidified water induces the mobilization of metals (Note: none above MCL)

<table>
<thead>
<tr>
<th>Concentration (ppm)</th>
<th>pH</th>
<th>As</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5</td>
<td>6</td>
<td>9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Concentration (ppb)</th>
<th>Fe</th>
<th>Mn</th>
<th>Ni</th>
<th>Cd</th>
<th>Ba</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1,000</td>
<td>2,000</td>
<td>10,000</td>
<td>50</td>
<td>200</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Concentration (ppm)</th>
<th>Mg</th>
<th>Ca</th>
<th>Sr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
<td>15</td>
<td>5</td>
</tr>
</tbody>
</table>
Metal concs varied ~ linearly with Calcium, suggesting a CaCO$_3$ source.
Mechanisms: Which mineral phases are the source of the metal release?

Sequential Extractions

Mobile
- Ion-exchangable
- Carbonate dissolution

Immobile
- Fe-Mn Oxides
- Sulfides, Organic Matter
Trace elements released from carbonate fraction

FCC1  Sr

Mobile Fraction

Carbonates

Ion Exchange

FCC1  FCC2  TMM
Trace elements released from carbonate fraction

Carbonates
Ion Exchange

Mobile Fraction

Concentration in rock (mg/kg)

Concentration in water (mg/kg)

Time (days)

Concentration in water (mg/kg)

Time (days)
Geochemical modeling of experimental data re-affirms hypothesis of carbonate dissolution
Summary: Lessons Learned

-Aquifer heterogeneities are important in risk calculations.

-Kinetic reactions with local dispersion result in lower peak concentrations, but earlier arrival and longer tails: higher calculated risk.

-Temporal risk calculations that consider longer exposure durations with smaller concentrations are important in evaluating the true risk.

-Brine leakage may increase for conditions where CO$_2$ leakage decreases (lower injection pressures, further distance from Fault) due to relative permeability-pressure considerations.

-Carbonate minerals in sandstones can buffer acidity during leakage into aquifers, but may also be the dominant source of mobile trace metals.

-In experiments, one aquifer rock resulted in exceeding secondary MCL for Fe and Mn: rock type is important!
Summary: Future Work

- Project ends this fall.

- Wrap up publication on multiphase modeling of brine and CO2 leakage (Menke) and hydrochemical changes from CO2 leakage into sandstone aquifers.


Theses Completed


Abstracts  More than 15:
American Geophysical Union Fall Meeting
Geological Society of America Annual Meeting
ASCE Environmental Water Resources Institute Annual Meeting
Goldschmidt Meeting on Geochemistry
National Ground Water Association Summit
Questions?
Organization Chart

John McCray, Principal Investigator

Reed Maxwell
co-PI

Alexis Navarre-
Sitchler, PM

Ralph Brown
Contracts,
ARRA
Reports

Erica Siirilla
PhD Student

Hannah Menke
MS Student

Katie Kirsch
MS Student
## Project Overview:
### Goals and Objectives: Tasks

<table>
<thead>
<tr>
<th>Task</th>
<th>Percent Complete</th>
<th>FY 2010</th>
<th>FY 2011</th>
<th>FY 2012</th>
<th>FY 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tasks 1: Project Management Plan and Reporting</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 Project Management Plan (PMP)</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 Planning and Reporting</td>
<td>90%</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Task 2: Quantifying risk associated with leakage of CO₂ into overlying aquifers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Lit review on CO₂ leakage and impacts on aquifer water quality</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.2 Lit review on toxicity of CO₂ leakage byproducts</td>
<td>100%</td>
<td></td>
<td></td>
<td>G</td>
<td></td>
</tr>
<tr>
<td>2.3 Identification of scenarios</td>
<td>90%</td>
<td>F</td>
<td>J</td>
<td>K</td>
<td></td>
</tr>
<tr>
<td>2.4 Risk assessment modeling</td>
<td>90%</td>
<td></td>
<td></td>
<td>N</td>
<td>P</td>
</tr>
<tr>
<td>Task 3: Laboratory experiments and associated modeling to elucidate pore-scale geochemical processes associated with carbon injection, storage and sequestration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1 Detailed sample characterization</td>
<td>60%</td>
<td>H</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.2 Laboratory experiments</td>
<td>60%</td>
<td></td>
<td></td>
<td>L</td>
<td></td>
</tr>
<tr>
<td>3.3 Reanalysis of samples from experiments</td>
<td>25%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.4 Geochemical modeling</td>
<td>10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Task 4: Seminar taught for course credit on risk-assessment associated with CO₂ sequestration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1 Develop course syllabus</td>
<td>100%</td>
<td></td>
<td></td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>4.2 Develop course materials</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td>M</td>
</tr>
<tr>
<td>4.3 Deliver Course</td>
<td>100%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Project Overview:

**Goals and Objectives:** Milestones

<table>
<thead>
<tr>
<th>Task/Subtask #</th>
<th>Project Milestone Description</th>
<th>Project Duration - Dec 2009 - Nov 2012</th>
<th>Planned Start Date</th>
<th>Planned End Date</th>
<th>Actual Start Date</th>
<th>Actual End Date</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2</td>
<td>A - Project Kickoff meeting</td>
<td>Q1: 12/1/09 Q2: 12/31/09 Q3: 12/1/09 Q4: 12/31/09</td>
<td>12/1/09</td>
<td>12/31/09</td>
<td>12/1/09</td>
<td>12/31/09</td>
<td>Completed as planned</td>
</tr>
<tr>
<td>1.2</td>
<td>B - Educational Program Instituted</td>
<td>Q1: 1/1/10 Q2: 6/30/10 Q3: 1/1/10 Q4: 6/30/10</td>
<td>1/1/10</td>
<td>6/30/10</td>
<td>1/1/10</td>
<td>6/30/10</td>
<td>Completed ahead of schedule</td>
</tr>
<tr>
<td>1.2</td>
<td>C - Semi-Annual Progress Report</td>
<td>Q1: 9/1/10 Q2: 9/30/10 Q3: 7/1/10 Q4: 7/31/10</td>
<td>9/1/10</td>
<td>9/30/10</td>
<td>7/1/10</td>
<td>7/31/10</td>
<td>Quarterly report for Q3 - 2010 FY serves as semi-annual report per email from Joshua Hull</td>
</tr>
<tr>
<td>1.2</td>
<td>E - Yearly Review Meeting</td>
<td>Q1: 9/30/12 Q2: 9/30/12 Q3: 4/1/10 Q4: 6/30/10</td>
<td>9/30/12</td>
<td>9/30/12</td>
<td>4/1/10</td>
<td>6/30/10</td>
<td>Completed as planned</td>
</tr>
<tr>
<td>2.3</td>
<td>F - Determine most probable leakage scenarios</td>
<td>Q1: 4/1/10 Q2: 6/30/10 Q3: 4/1/10 Q4: 6/30/10</td>
<td>4/1/10</td>
<td>6/30/10</td>
<td>4/1/10</td>
<td>6/30/10</td>
<td>Completed as planned</td>
</tr>
<tr>
<td>2.2</td>
<td>G - List of EPA-regulated byproducts of reaction between aquifer materials and CO2</td>
<td>Q1: 4/1/10 Q2: 12/31/10 Q3: 4/1/10 Q4: 9/30/10</td>
<td>4/1/10</td>
<td>12/31/10</td>
<td>4/1/10</td>
<td>9/30/10</td>
<td>Completed ahead of schedule</td>
</tr>
<tr>
<td>3.1</td>
<td>H - Initial characterization of injection and caprock formation begun</td>
<td>Q1: 1/1/10 Q2: 12/31/10 Q3: 1/1/10 Q4: 12/31/10</td>
<td>1/1/10</td>
<td>12/31/10</td>
<td>1/1/10</td>
<td>12/31/10</td>
<td>Completed as planned</td>
</tr>
<tr>
<td>4.1</td>
<td>I - Development of course syllabus complete</td>
<td>Q1: 12/1/10 Q2: 8/15/11 Q3: 11/1/10 Q4: 8/1/11</td>
<td>12/1/10</td>
<td>8/15/11</td>
<td>11/1/10</td>
<td>8/1/11</td>
<td>Completed as planned</td>
</tr>
<tr>
<td>4.1</td>
<td>J - Identify and rank aquifer sites for use in risk simulations complete</td>
<td>Q1: 7/1/10 Q2: 3/31/11 Q3: 1/1/10 Q4: 3/31/11</td>
<td>7/1/10</td>
<td>3/31/11</td>
<td>1/1/10</td>
<td>3/31/11</td>
<td>Completed as planned</td>
</tr>
<tr>
<td>2.3</td>
<td>K - Identify and rank aquifer-leakage scenarios for use in risk simulations complete</td>
<td>Q1: 10/1/10 Q2: 6/30/11 Q3: 10/1/10 Q4: 6/30/11</td>
<td>10/1/10</td>
<td>6/30/11</td>
<td>10/1/10</td>
<td>6/30/11</td>
<td>Completed as planned</td>
</tr>
<tr>
<td>3.2</td>
<td>L - Determine rate parameters of important geochemical reactions</td>
<td>Q1: 7/1/10 Q2: 6/30/11 Q3: 7/1/10 Q4: 6/30/11</td>
<td>7/1/10</td>
<td>6/30/11</td>
<td>7/1/10</td>
<td>6/30/11</td>
<td>Completed as planned</td>
</tr>
<tr>
<td>4.3</td>
<td>M - Summary on demographics and grades for the university course</td>
<td>Q1: 6/1/11 Q2: 12/31/11 Q3: 8/1/11 Q4: in progress</td>
<td>6/1/11</td>
<td>12/31/11</td>
<td>8/1/11</td>
<td>in progress</td>
<td>in progress</td>
</tr>
<tr>
<td>2.4</td>
<td>N - Complete screening risk assessment simulations</td>
<td>Q1: 7/1/11 Q2: 6/30/12 Q3: 7/1/11 Q4: 6/30/12</td>
<td>7/1/11</td>
<td>6/30/12</td>
<td>7/1/11</td>
<td>6/30/12</td>
<td>Completed as planned</td>
</tr>
<tr>
<td>3.4</td>
<td>O - Complete geochemical modeling for relevant carbon injection scenarios</td>
<td>Q1: 10/1/11 Q2: 11/30/12 Q3: 10/1/11 Q4: in progress</td>
<td>10/1/11</td>
<td>11/30/12</td>
<td>10/1/11</td>
<td>in progress</td>
<td>in progress</td>
</tr>
<tr>
<td>2.4</td>
<td>P - Complete primary risk simulations for aquifer leakage</td>
<td>Q1: 7/1/12 Q2: 11/30/12 Q3: 7/1/11 Q4: in progress</td>
<td>7/1/12</td>
<td>11/30/12</td>
<td>7/1/11</td>
<td>in progress</td>
<td>in progress</td>
</tr>
</tbody>
</table>