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Abstract

Surface and near-surface environmental conditions are being monitored at the Frio Brine Pilot site near Dayton, Texas, in order to detect potentially significant leaks of CO_2 and associated perfluorocarbon tracers that were injected on October 4, 2004, into Frio Formation sandstone at 5,050-ft depth. In-field measurements and sampling for laboratory analyses of shallow groundwater and gases that accumulate in water-well headspaces and soils are ongoing through cooperative efforts. The site is in a 50-year-old-oilfield with a shallow water table in clay soils. The area is partly cleared, flood-tolerant woodland. Fluvial siltstone and sandstones provide higher permeability in the near-surface zones. Shallow Beaumont Formation groundwater hydrochemistry and headspace gases are being monitored in four 95-ft wells by field probes, laboratory analyses, and capillary absorption tubes (CATs). Soil gases are sampled by hypodermic syringe in four 5-ft-deep, sealed dry wells in the vadose zone; by CATs placed in 40 0.3- to 1-meter-deep tubular aluminum installations; and by a portable accumulation chamber from which gases are collected. Shallow-groundwater pH, electrical conductivity, and alkalinity have varied since injection, However, unambiguous evidence is lacking that suggests leakage of CO_2 and CH_4, and variable meteoric conditions may be responsible for observed hydrochemical variability at the site. Results of post-injection groundwater and soil-gas analyses are pending.

Introduction

One of the key criteria for successful storage of carbon dioxide is acceptable integrity of the storage environment, i.e., the target reservoir must not leak the stored gases over extended periods of time. Surface and near-surface environments are logical places to monitor for leaks from depth. In the event of significant leakage to the surface it is expected that shallow groundwater and soil-gas chemistry would deviate from established background characteristics. Carbon dioxide and other gases in the storage reservoir (including introduced tracers) might be expected to invade shallow environments at detectable concentrations. The effects on shallow groundwater would include decreases in pH as higher concentrations of carbonic acid developed and increases in alkalinity as mineral dissolution accelerated.

The first requirement for successful monitoring, once the design of the monitoring program is finalized and the various devices are installed and procedures implemented in the monitoring environments, is to develop baseline data over a sufficiently long time to establish normal background variations of the chosen analytes. Normal variations result from shorter- and longer-term climatic effects that include meteorological events and seasonal impacts. Both these aspects influence vegetation types and abundance. High frequency or continuous monitoring of certain, if not all, environmental indicators may be the only way to fully develop a reliable database of background variations. Automated continuous logging in groundwater of specific conductivity, pH, temperature, and water level is easily conducted and relatively inexpensive.

Anthropogenic influences also may need to be accounted for, which would necessitate monitoring certain local industries that produce and discharge analytes similar to those being monitored at the test site. Additionally, normally routine operations at the test site can introduce (often inadvertently) additional variables that may affect measurements. Drilling, cementing and perforation operations, pumping water into and out of test wells and holding ponds, venting of test-well gases, and temporary disturbance of monitoring installations can affect the integrity of environmental data. Site operators may not be knowledgeable with regard to their influence on environmental monitoring. The consequences of such disturbances may be difficult to evaluate even if the potentially interfering activities are recognized. One significant aspect of this interference is producing CO_2 for sampling and releasing gas and included tracers to the atmosphere, thereby contaminating the site for leakage monitoring.

Development of a comprehensive pre-injection monitoring program that satisfies the criteria mentioned above is challenging . Not only is considerable deliberation imperative so that all contingencies are anticipated, but the budgetary demands for personnel, equipment, and analytical services may be daunting. The need for discipline among the personnel responsible for implementing the program is absolute if reliable data are to be developed.

As if the task introduced briefly in forgoing discussion is not sufficiently intimidating, some environments are particularly challenging to monitor because there is likely to be a lot of natural background carbon dioxide. The Frio test site in eastern Texas is such a site because it is forested, receives abundant rainfall, and is relatively warm most of the year. The production of carbon dioxide by decay of organic matter is

probably quite elevated. The analytical challenge may be recognizing a subtle leakage signal within abundant background noise.

Surface Monitoring at the Frio CO2 Test Site

The ultimate objective of surface monitoring at the site is to detect CO_2 that leaks from the Frio Fm. injection interval at 5,050 ft depth. The gas, if sufficiently concentrated, may be detected in either or both the groundwater as a dissolved phase or the unsaturated zone as a free gas. The most likely potential avenues for CO_2 migration to the shallow subsurface in the experiment area are via the annular zones that are adjacent to the casings associated with the experimental injection and observation wells. However, geologic avenues are also plausible.

Several chemical tracers were mixed with the CO_2 during injection into the Frio C-sand to provide unambiguous evidence that any CO_2 detected at the surface originated from the injected material. These tracers include perfluorocarbons that would sorb to absorbent fibrous elements (capillary absorbent tubes, or CATs) placed in surface installations. CATs were installed by NETL researchers in both the unsaturated zone to monitor soil gas and in the saturated zone to monitor groundwater. CATs are periodically removed from installations and analyzed for sorbed constituents. Additionally, the presence of sufficiently elevated concentrations of CO_2 in groundwater is expected mainly to lower pH beyond the normal range that was determined during pre-injection monitoring.

The goal of the NETL measurement, monitoring, and verification (MM&V) program, called ‘SEQURE Technologies” is to provide techniques to evaluate the stability, capacity, rate of leakage, and permanence of carbon dioxide stored in geologic formations. The objective is to evaluate a number of surface and near- surface monitoring techniques that show promise in the detection of both the short term, rapid loss, and long term, slow leakage of carbon dioxide from geologic formations. One of the techniques being evaluated is the spiking of CO_2 with perfluorocarbon tracers (PFTs) during injection, followed by the monitoring of soil-gas for the presence of PFTs that have migrated along with CO_2 to the surface. Following injection, PFTs are also monitored in shallow aquifer water wells, and in the atmosphere at the injection site for the presence of PFT plumes that might be indicative of leakage. Details of the Frio, saline aquifer, sequestration project will not be discussed here as they are available elsewhere.

PFTs have a number of distinct advantages for this work such as complete solubility in CO_2, non-toxic, non-radioactive, and most importantly, they have a detection limit in atmospheric and soil-gas samples in the parts per quadrillion range. This means that much smaller amounts need to added to the CO_2 when compared to tracers such as sulfur hexafluoride to achieve the same level of detection at the surface. PFTs have been previously used primarily in the atmosphere for environmental and meteorological studies. The sensitivity of the technique required that a demanding protocol, including the physical separation of the tracer injection team from the monitoring team, be used to avoid cross-contamination of the CATs.

Three PFTs were injected into the CO_2 stream at the well head during 3 tracer injection periods, with 500 mls of a single tracer added during each tracer injection period. The tracer injection periods were 12 hours for the first and second tracers, and 6 hours for the last tracer. The first and second tracers were added one after the start of the first and second CO_2 injection periods respectively. The third tracer was added on the third day of the second CO_2 injection period. Monitoring included a soil-gas matrix and an atmospheric matrix, 2 soil-gas profiling arrays, monitoring in 3 shallow aquifer water wells and in the headspace above the water wells, and hand syringed atmospheric samples. Separate personnel were used as part of a program to minimize risk of contamination .

Tracer analysis involves thermal de-sorption of tracers from the CATs, with GC, electron capture detection and is performed at the Brookhaven National Laboratories Tracer Technology Center, who also supplies us with CATs. A great deal of analytical pretreatment is required to remove hydrocarbons, Freons, and other soil and air-gas contaminates to obtain the needed detection limit. Results from CAT installations that have been retrieved from the site since CO_2 injection are pending.

Monitoring Installations

Four methods of surface and near-surface monitoring were designed to monitor the saturated (groundwater) and unsaturated (soil) zones:

(1) For groundwater monitoring four 95-ft-deep wells (fig. 1) were installed along the perimeter of the experiment staging area or pad. One of the wells is located up-hydraulic gradient of the Frio

observation well, while the remaining three wells are located in down-gradient positions (fig. 2). The aquifer interval at this depth is the

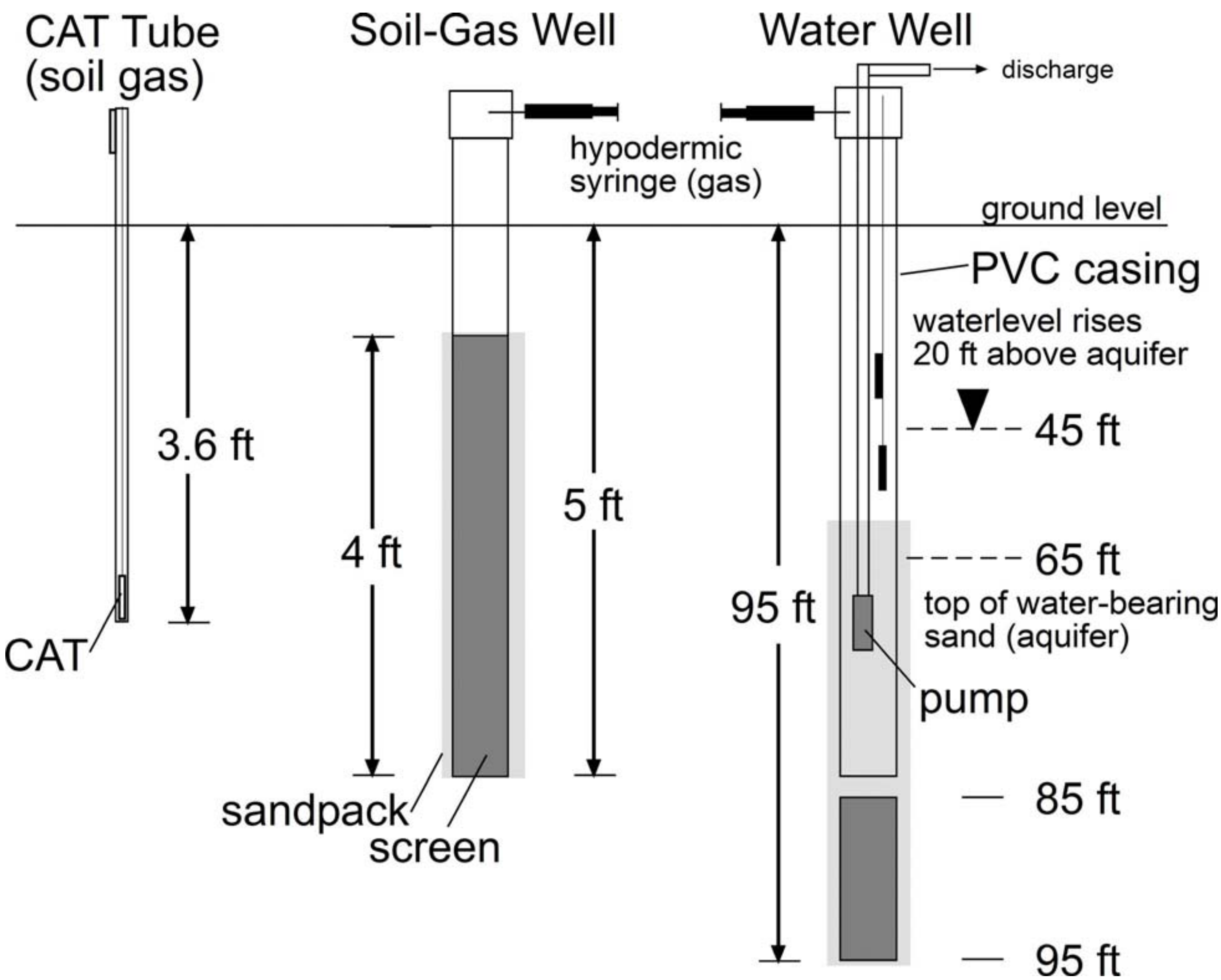

Figure 1. Diagrams of three shallow and near-surface environmental monitoring installations at the Frio test site.

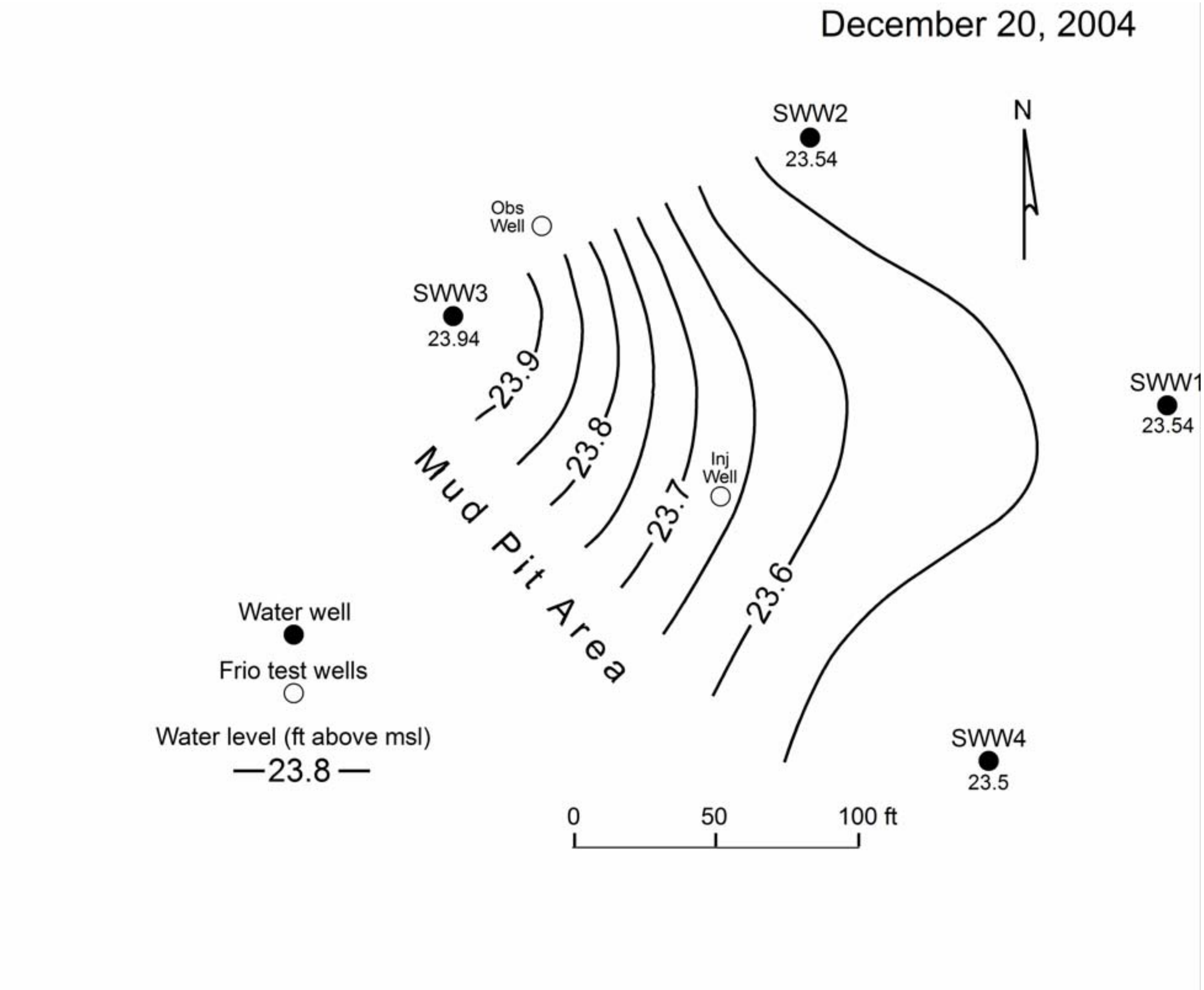

Figure 2. Potentiometric surface map (December 20, 2004) and locations of shallow Beaumont Formation aquifer water wells and Frio test wells at the Frio Pilot Project site near Dayton, Texas.

Pleistocene-age Beaumont Formation, a member of the Gulf Coastal Chicot aquifer system. The shallowest aquifer interval at the site is at 60-85-ft depth in fine-to-medium grained sand that has gravel at the base of the interval. When the sand interval is penetrated the water level in the well rises to approximately 40-45 ft depth in the borehole, thus suggesting that the aquifer interval is somewhat confined by an overlying clay-bearing silt that extends to the surface. The wells are cased with 4-in-dia PVC tubing with a 10-ft-long screen installed at 85-95-ft depth in the coarser-grained section of the water-bearing

sand interval. The casing bases are fitted with caps that include one-way check valves that allowed purging of the well of fine-grained debris during completion. The casing extends approximately 2 ft above ground level and is fitted on top with a PVC cap. In the caps are cemented rubber scepta that allow access to the headspace with a hypodermic syringe and a stainless eye-hook for suspending CAT devices. A 3-ft x 3-ft x 6-in poured concrete pad is installed abound the casing. A locking steel header is installed in the concrete. The installation was designed to isolate the borehole environment from the atmosphere so that only constituents from the subsurface would accumulate in the well.

(2) For soil-gas and atmospheric monitoring matrices were designed to cover a roughly circular area around the injection well of 400 meters diameter, and to monitor nearby wells and geological features that might represent possible sources of leakage. Included in this survey were 15 wells and 2 features of geologic interest. Monitors were also located near the direct CO_2 flux monitoring locations. The soil-gas monitors are steel pipe, detachable-head penetrometers, designed by NETL, which were driven into the soil to a depth of 1 meter (fig.1). Sorbent packets (CATs) are left in the monitors to collect tracers present in soil-gas. Some of the monitors include atmospheric samplers as well. Two depth profiling arrays that sample soil-gas from the near surface to 2 meters are located just off the injection well pad to the north and east. Including the water well monitors, a total of 62 CATs are periodically exchanged at the same time 4 to 10 hand syringed atmospheric samples are taken. Samples were taken for a week prior to injection for background measurements, and for a week after the start of injection. Additional post-injection samples are being taken at 1 ½ to 3 month intervals.

(3) LBNL researchers designed shallow wells for deployment in the unsaturated zone to collect soil-gases (fig. 1). For soil-gas monitoring to approximately 2-m-depth four shallow dry wells were augured manually to 1.5 m (5 ft), which is the length of the auger. In each well 4-in-dia PVC casing was installed with a 4-ft-long screen on the lower part. The casings extend approximately 3 ft above ground level and were secured with a 3-in-thick, 2-ft-dia poured concrete pad. The

casings are fitted with PVC caps into which rubber scepta are cemented for access to the headspace with a hypodermic syringe.

(4) For gases diffusing into the atmosphere from the ground and low-profile vegetation researchers from NETL and the Colorado School of Mines deployed a box-like Plexiglas chamber from which accumulated gases were collected and analyzed. A total of 22 locations were chosen throughout the area focusing mainly near the pad of the injection well. All locations are collocated with perfluorocarbon tracer measurements (CATS locations). At each location three measurements of the CO_2 soil gas flux were made using one meter square accumulation chambers sealed to the soil surface. CO_2 concentration was measured continuously under the chambers to determine the flux. In addition, the CH_4 flux was determined by taking gas samples from under each chamber at regular intervals and analyzing with gas chromatography. Also at each location, soil gas samples were taken at various depths up to 1 meter to determine the CO_2 and CH_4 concentration depth profile. Stable carbon isotope ratios of CO_2 were also determined on soil gas samples in order to distinguish deep sourced CO_2 from biological source background. Soil gas radon measurements were also made to provide an additional indicator for gas flow to the surface. A full survey was conducted in February of 2004 (pre-injection) as well as February 2005 (post injection).

Sampling

Groundwater, water-well headspace atmosphere, and soil-gas are sampled periodically by several methods. Some samples are partly analyzed in the field (groundwater) and the remaining samples (groundwater and atmosphere) are packaged and shipped to appropriate laboratories for further analyses. Sampling of gases and groundwater wells was conducted on approximately a monthly basis.

Shallow Water Wells

Groundwater and headspace atmosphere is sampled from the four shallow water wells. For headspace sampling a rubber scepta is cemented

to the opening of a 10 ml glass vial. A hypodermic needle is attached to a 10cc glass gas-tight syringe whose plunger is fully inserted such that no space occurs between the plunger and the needle base. The labeled vial is evacuated with the syringe three times. This is assumed to reduce the ambient vial atmosphere by 98%. Thereafter, two syringe-full volumes of well head-space atmosphere obtained through the wellhead scepta are injected into the vial. A thin silicone disk is then cemented to the top of the vial scepta.

For use of a comparative sampling technique the scepta is then withdrawn from the wellhead. Into the opening a plastic tube is inserted that is connected to a gas pump. The pump is activated and fills a labeled gas-tight plastic bag with well head-space atmosphere. The scepta is then re-cemented to the well cap.

The cap is then removed from the wellhead, the CAT suspension line is wound up, and the CATs are sealed in a nalgene bottle. If desired the CATs may be removed for analysis of absorbed constituents. A variable-speed water pump is lowered into the well to a depth approximately 40 ft below the water surface. After pumping for 1-2 hr at a rate of 2.8 to 8.3 gpm (depending on specific capacity of the well) several volumes of water are collected at the discharge point and then removed to the field lab where two volumes are chemically stabilized by using standard procedures for deferred cation analyses. One volume is stored without chemical additives for anion analysis. Specific conductivity and pH are measured in the field and alkalinity is determined by titration with dilute HCl. CATs are replaced (if required) or returned to their original suspended configurations, and the well is recapped.

Soil-Gas Wells

The soil-gas well atmosphere is sampled through attached rubber scepta with a hypodermic syringe by the same method used to sample water-well head-space atmosphere (fig.1).

Cat Installations

Periodically CATs are removed from the aluminum tubes and shipped to an appropriate laboratory for analyses of sorbed constituents. Fresh CATs are installed and tubes are re-sealed.

Measurements of Groundwater Parameters

Aquifer characterization has included both hydrodynamic and hydrochemical components. A recent pump-test was conducted at the site whereby SWW2 was pumped for 4h at 8.33 gpm while water levels were measured at SWW1 and SWW4 at regular intervals (fig 3). Specific conductivity, pH, temperature, and alkalinity measurements that were conducted in the four shallow groundwater wells have documented noteworthy hydrochemical differences between the wells at each monthly sampling episode and also month-to-month variations over the 9-month monitoring period that began in July 2004 (Table).

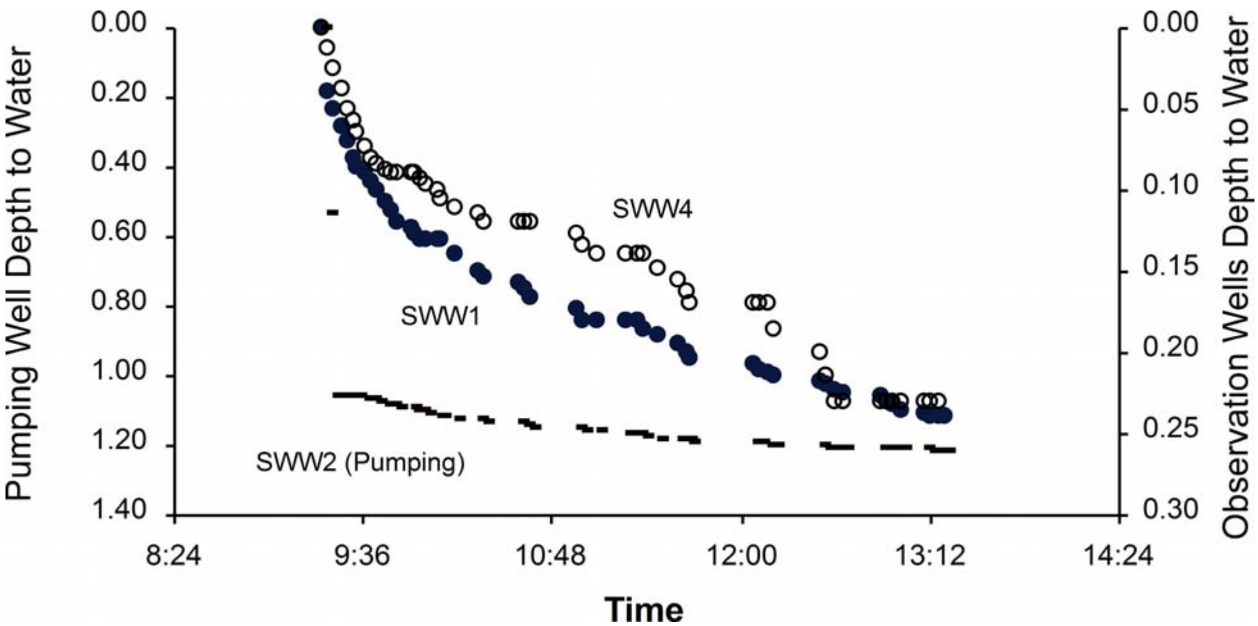

Figure 3. Graph of data collected during a four-hour pump test conducted at SWW2.

Table. Analyses of Beaumont Formation groundwater from the Frio Test Site.

Well	Collection Date	EC	pH	HCO_3^-	F^-	Cl^-	NO_2^-	Br^-	NO_3^-	$SO_4^{=}$	Al	Ca	Fe	K	Mg	Mn	Na	Si	TDS	Ca/Cl	Mg/Cl	Na/Cl	Br/Cl X 10^4
		µS/cm	s.u.	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	µg/L	mg/L	mg/L	mg/L	mg/L	µg/L	mg/L	mg/L	mg/L	mass units			
SWW #1	10/1/2004	681.0	7.24	373.8	0.25	25.6	1.12	<	<	0.25	43	91.0	1.99	1.81	9.59	313	44.2	10	559.9	3.55	0.37	1.72	nd
	10/29/2004	628.0	7.20	367.5	0.25	26.6	1.11	<	<	0.30	13	90.4	2.21	1.78	9.52	302.67	43.6	9.7	553.3	3.40	0.36	1.64	nd
	11/23/2004	634.0	7.16	384.1	0.25	31.9	1.10	<	<	0.51	43	93.0	2.36	1.67	9.59	300	42.6	9.7	577.0	2.91	0.30	1.33	nd
	12/20/2004	755.0	7.11	377.5	0.21	93.2	<	0.10	1.28	0.80	28	120	2.81	1.77	12.5	391	42.9	8.9	662.5	1.29	0.13	0.46	11.13
	2/16/2005	1375	7.05	366.9	0.20	248	1.68	<	<	1.06	<	167	3.98	1.82	17.3	549.5	42.4	8.5	858.9	0.67	0.07	0.17	nd
	4/4/2005	1171	6.88	357.6	0.21	215	<	0.2233	<	0.75	42	181	4.47	2.07	18.6	594.5	46.0	8.9	834.8	0.84	0.09	0.21	10.39
SWW #2	10/1/2004	696.0	7.16	363.9	0.29	32.1	<	<	1.08	<	12	81.7	1.38	1.80	8.55	285.67	57.8	10	559.1	2.54	0.27	1.80	nd
	10/29/2004	722.0	7.25	353.1	0.29	35.7	0.92	<	<	0.26	41	81.5	1.29	1.91	8.60	271.67	57.9	10	551.9	2.28	0.24	1.62	nd
	11/23/2004	621.0	7.13	377.4	0.29	32.2	<	<	<	0.32	48	81.6	1.79	1.71	8.45	265	57.1	10	571.3	2.53	0.26	1.77	nd
	12/20/2004	1173	7.19	360.8	0.28	31.1	<	<	1.08	<	36	79.4	1.70	1.51	8.34	265	54.3	9.2	548.1	2.55	0.27	1.75	nd
	2/16/2005	4730	6.82	393.9	<	1387.05	1.31	<	<	15.4	<	661	14.1	3.52	35.2	1255	168	11	2691.6	0.48	0.03	0.12	nd
	4/4/2005	3240	6.72	386.9	<	902	<	0.84	<	7.01	90	486	8.40	2.38	20.8	566	133	10	1957.5	0.54	0.02	0.15	9.35
SWW #3	10/1/2004	3440	6.70	440.0	<	834	0.51	3.13	<	15.3	52	533	3.21	2.11	23.9	1606.7	120	12	1988.9	0.64	0.03	0.14	37.54
	10/29/2004	3000	6.67	454.7	<	672	<	3.45	<	15.5	24	441	2.54	1.64	17.9	1260	94.9	12	1717.5	0.66	0.03	0.14	51.40
	11/23/2004	2620	6.59	475.9	<	640	<	5.36	<	18.5	49	453	0.45	1.17	15.4	1385	85.2	12	1708.2	0.71	0.02	0.13	83.75
	12/20/2004	3700	6.55	456.6	<	1027	<	4.95	<	18.0	69	605	0.62	1.28	20.0	1458	123	12	2269.4	0.59	0.02	0.12	48.21
	2/17/2005	5040	6.70	431.6	<	1438.45	<	4.13	<	17.5	<	688	0.64	1.97	27.2	848.5	192	12	2814.0	0.48	0.02	0.13	28.70
	4/4/2005	4130	6.52	405.5	<	1141.22	<	11.9	<	19.4	110	650	0.83	1.85	23.2	1530	172	11	2437.8	0.57	0.02	0.15	104.42
SWW #4	10/1/2004	777.0	7.16	372.3	0.24	62.6	1.05	<	<	1.42	13	107	2.51	2.01	10.5	364	46.5	10	617.0	1.71	0.17	0.74	nd
	10/29/2004	757.0	7.08	372.2	0.26	66.9	1.17	<	<	1.70	16	112	2.79	1.76	10.9	384.33	46.5	10	627.1	1.68	0.16	0.69	nd
	12/20/2004	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
	11/23/2004	716.0	7.18	371.8	0.23	59.6	<	<	<	1.37	52	111	2.66	1.72	10.7	368	44.1	11	613.6	1.85	0.18	0.74	nd
	2/17/2005	1411	7.03	408.2	<	249.97	<	0.27	<	7.07	<	199	5.19	1.66	13.7	611.5	35.9	11	931.7	0.79	0.05	0.14	10.69
	4/4/2005	1208	6.88	371.0	0.20	203	<	0.22	<	5.51	44	197	4.92	1.80	13.7	608.5	41.4	9.8	848.7	0.97	0.07	0.20	10.93
Frio Inj Well	6/16/2004	105800	6.8	192	nd	43940	nd	59	nd	77	<100	2222	<10	142	379	2.2	24805	27	215867	0.05	0.01	0.56	13.51
Frio Obs Well	6/16/2004	104300	6.8	194	nd	43640	nd	61	nd	78	<100	2221	<10	147	388	2.3	25034	27	214313	0.05	0.01	0.57	14.00

Table. Chemical analyses and calculated ionic ratios for groundwater collected from the shallow- and Frio-test wells. Frio data are from samples that pre-date carbon dioxide injection of October 2004 at the site.

The shallow well (SWW3) that is located closest to the Frio test observation well is quite distinctly more saline than the other three wells (fig. 4, Table). It also shows consistently lower pH, higher alkalinity. It also has a distinctly lower specific capacity than the other wells. The hydrochemical distinctions are probably related to its location near the Frio well which was originally drilled in the 1950's and produced oil from a Yegua Formation reservoir at several thousand feet depth below the Frio interval. It is not known what the exact causes of the contamination of the shallow well are. There was a reserve pit next to the oil well that received produced brine (no, we tested it). The lower specific capacity of the well probably owes to the fluvial depositional fabric of the Beaumont Formation within which the wells are completed. It was noted during drilling of the wells that SWW3 was distinctly finer-grained in the sand-dominated completion interval and lacked the conspicuous gravel fraction that was present in the other wells. This suggests that the more-productive wells were completed is locations more proximal than was SWW3 to a Beaumont fluvial channel axis where permeability is expected to be higher.

The other three shallow wells are hydrochemically more similar to each other than to SWW3. For example, average Na/Cl values range from 1.2-2.8 (in equivalent units) at SWW1, SWW2, and SWW4; while the average Na/Cl at SWW3 is 0.22, a value closer to that of Frio brine. Ca/Cl and Mg/Cl values also show relative chemical affinities between SSW3 and Frio brine, as demonstrated by the baseline data developed in July 2004 (fig. 5). However, SWW2 has become significantly more saline in recent months (Table). The Na/Cl at SWW2 has fallen from a high of 1.8 to a recent value of 0.15 (the same as SWW3) that marks a significant increase in chloride relative to sodium, although both have increased along with TDS. The increasing salinity, decreasing pH, and other chemical changes of SWW2 water may mark migration of a saline plume from the vicinity of SWW3. The highest hydraulic head is reported from SWW3, and SWW2 is the nearest down-gradient well (fig. 2). Migration of a saline plume that originates in the vicinity of SWW3 might be expected to be observed at SWW2 before the other shallow wells. Given the brief period of monitoring it is not possible to know if the salinity changes observed in the shallow the nearest down-gradient well (fig. 2). Migration of a saline plume that originates in the vicinity of SWW3 might be expected to be observed at SWW2 before the other shallow wells. Given the brief period of monitoring

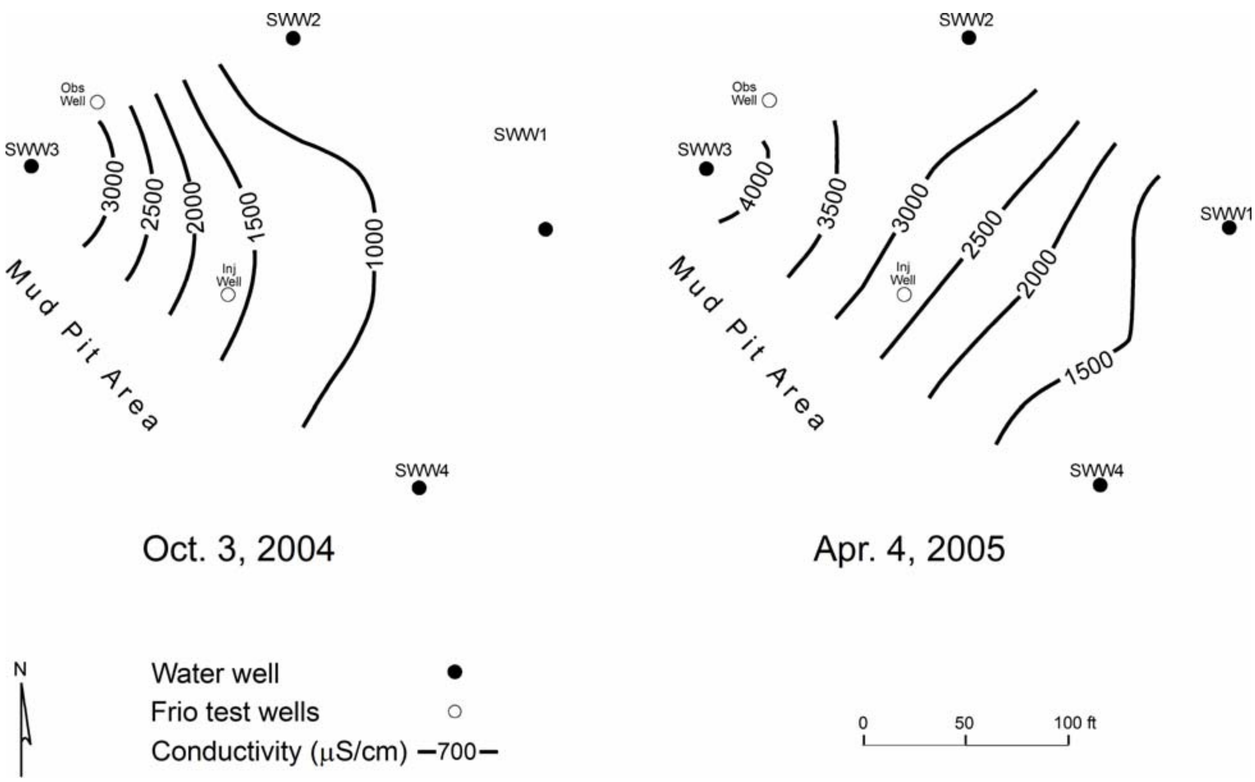

Figure 4. Maps of specific electrical conductivity of groundwater in the shallow wells for dates that pre-date and post-date carbon dioxide injection into the Frio Formation at the test site. Trend suggests down-hydraulic-gradient spread of a saline plume originating in vicinity or up-gradient of SWW 3.

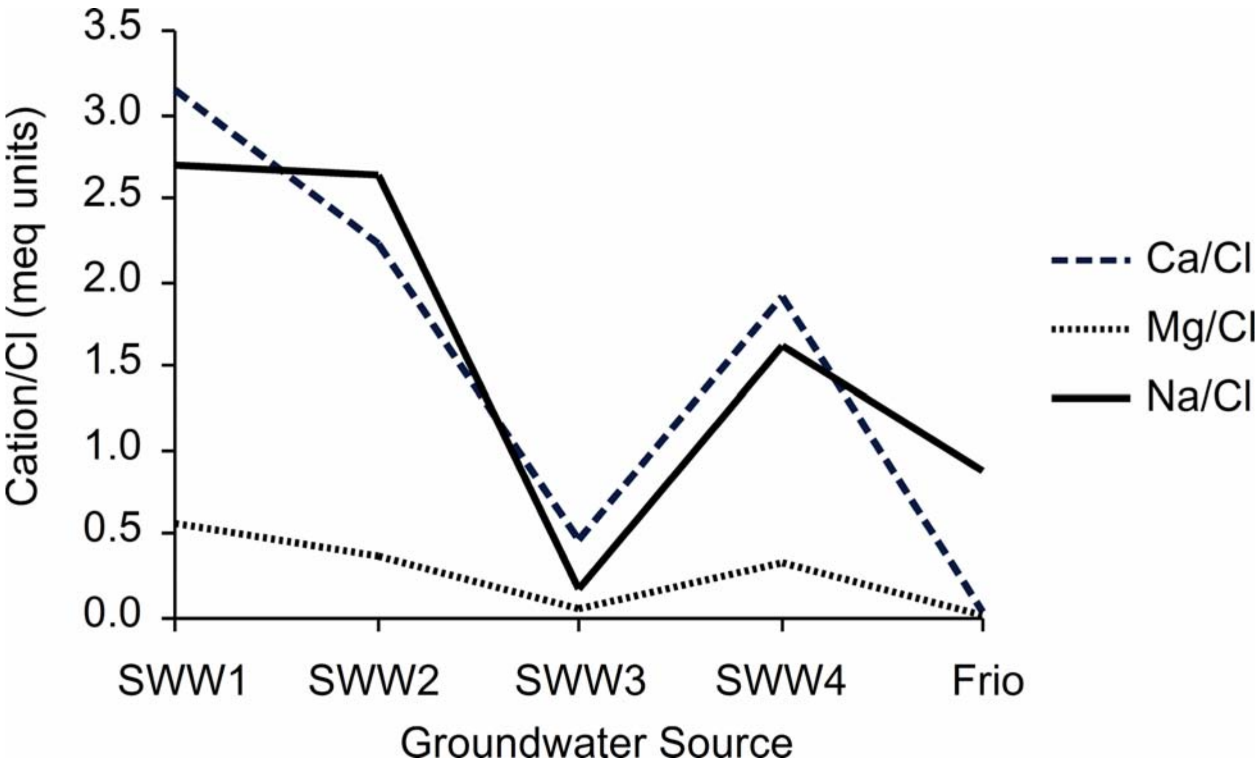

Figure 5. Graphs of cation/Cl average values calculated from analyses of Beaumont Formation groundwater sampled at the Frio test site (Table).

it is not possible to know if the salinity changes observed in the shallow wells is part of a normal cycle or an anomaly caused by test site operations. Operations on and around the staging area for the Frio test have introduced hydrodynamic factors that were not present previously. For example, a large pit for surface disposal of fresh water mud and cuttingswith an approximate depth of 1.5 m was constructed on the southwest side of the site and is located within several feet of SWW3 (fig. 2). The pit fills when rainfall is abundant. Water from the pit is episodically pumped from the pit into an adjacent area which is located immediately west of SWW3.

The higher hydraulic head and higher concentrations of carbon

dioxide measured in SWW3 groundwater may well be related to maintenance of a reservoir of water in the mud pit or pumping of water from the mud pit into the heavily vegetated area nearby. However, carbon-isotope analyses indicate negative $\delta^{13}C$ values for the carbon dioxide from the shallow groundwater and also for the carbon dioxide that was injected into the Frio. Results from tracer tests may resolve the issue of the ultimate source of the increased carbon dioxide content in SWW3.

Summary

Designing and maintaining a sufficiently comprehensive environmental monitoring program at a carbon dioxide storage site demands deliberation and planning in order to implement requisite fail-safe procedures, and a significant investment of human and material resources. Pre-injection baseline data must be developed over time intervals of sufficient length in order to document natural cyclic and episodic variations in environmental parameters that are determined to be key for purposes of detecting CO_2 -reservoir leakage to the shallow sub-surface and surface environments. Heavily vegetated, temperate, marginal wetlands sites such as the Frio test site will present special challenges because they naturally produce high levels of carbon dioxide from abundant decaying organic matter.

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