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Preinjection reservoir fluid characterization at a CCS demonstration site: Illinois Basin – Decatur Project, USA

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Abstract

The Midwest Geological Sequestration Consortium is conducting the Illinois Basin – Decatur Project (IBDP), a large-scale carbon capture and storage (CCS) project in Decatur, Illinois, USA. An extensive Monitoring, Verification, and Accounting (MVA) program has been implemented, and a deep monitoring well, VW#1, was drilled to a depth of 2,201 m (7,264 ft). The well was perforated in eleven zones ranging in depth from 1,499 to 2,153 m (4917 to 7061 ft.). Fluid samples were collected during three sampling events using two different sampling methods. This paper describes the well construction, well completion, sample collection procedures, and selected preinjection sampling results from VW#1. Prior to sampling, particular care was taken to remove non-native fluids from each of the sampling zones. Density, specific conductance, bromide concentrations, and bromide-chloride ratios have been used as indicators of sample representativeness.

Fluid compositional data and formation pressure data have been collected from VW#1. These high-quality, field-based data are essential to establish hydrochemical conditions in and above the storage reservoir prior to CO₂ injection, indicate the response of the reservoir to injection, provide detailed geochemical model inputs, and provide insights for on-going work at the Illinois State Geological Survey about the origin of Illinois Basin brines. Primary brine constituents are chloride, sodium, and calcium with average total dissolved solids concentrations of 190,000 mg/L in the Mt. Simon Sandstone and 65,600 mg/L in Ironton-Galesville Formation (above the injection reservoir).

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1. Introduction

The Midwest Geological Sequestration Consortium is conducting the Illinois Basin – Decatur Project (IBDP), a large-scale carbon capture and storage (CCS) project in Decatur, Illinois, USA (Fig. 1a). The project will demonstrate the ability of a deep saline formation to store one million tonnes of carbon dioxide (CO₂) from an ethanol production facility. In November 2011, injection of CO₂ began at a rate of 1,000 tonnes/day into the Mt. Simon Sandstone at a depth of 2,129 to 2,149 m (6,985 to 7,050 ft). Injection will continue for three years.

An extensive Monitoring, Verification, and Accounting (MVA) program has been implemented and is focused on the 0.65 km² (0.25 mi²) project site (Fig. 1b). Goals of the program include establishing baseline conditions to evaluate the effects of CO₂ injection, demonstrating that project activities are protective of human health and the environment, and providing an accurate accounting of stored CO₂. MVA efforts were conducted pre-injection and will continue through the injection and post-CO₂ injection phases of the project. This paper describes the well construction, well completion, sample collection procedures, and selected preinjection sampling results from a reservoir monitoring well, named VW#1, that is located 305 m (1000 ft) north of the CO₂ injection well, CCS#1.

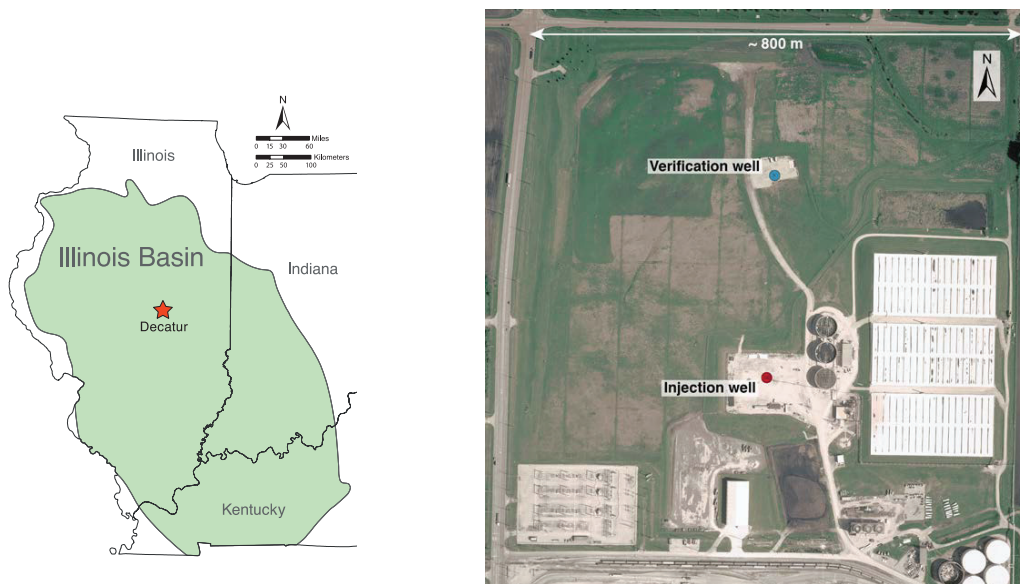


Fig. 1. Illinois Basin – Decatur Project location (left) and study site map (right) with the injection and verification wells.

2. Methods

2.1. Well drilling, construction, and completion

Well VW#1 was drilled to a depth of 2,201 m (7,264 ft). A total of three casing strings were used. The surface casing (340 mm diameter, 90.77 kg/m; 13-3/8 inch diameter, 61 pound/foot) was installed to a

depth of 107 m (350 ft) and cemented to surface. A 311 mm (12-1/4 in.) hole was drilled to 1,618 m (5,310 ft). The intermediate casing (244 mm diameter, 64.73 kg/m; 9-5/8 in., 40 lb/ft) was installed to 1,618 m (5,307 ft) and cemented to surface in two stages. The well was then drilled to a total depth (TD) of 2,201 m (7264 ft) with a 216 mm (8-1/2 in.) bit. The long string casing (140 mm diameter, 25.3 kg/m; 5-1/2 in., 17 lb/ft) was installed to 2,213 m (7,260 ft). The lower 675 m (2,215 ft) of the casing was constructed with 13% chromium stainless steel, a corrosion-resistant alloy. The long string was cemented back to surface in a single stage with CO₂ resistant cement used from TD to 1,448m (4,750 ft) below land surface. Well completion activities occurred 6 months after the well was cased. During perforation, the well contained a synthetic sodium chloride (NaCl) completion fluid with a density of 1.107 g/cc (9.2 pound per gallon). Perforation was done over eleven zones ranging in depth from 1,499 to 2,153 m (4,917 to 7,061 ft). One zone is in the rhyolitic basement, eight zones are in the injection reservoir (Mt. Simon Sandstone), and two zones are in the first porous and permeable formation (Ironton-Galesville Formation) above the primary seal. Zones numbers increase with decreasing depth. The zone in the rhyolitic basement (zone 1) has relatively low permeability and is used only for pressure monitoring.

2.2. Swab sampling and analytical methods

In May 2011, VW#1 was perforated. Swab testing began immediately and lasted for 14 days. Zones were individually swab tested from deepest to shallowest using a packer and a retrievable bridge plug. Produced fluids were collected at the well head as frequently as every 15 minutes and periodic tests were conducted in the field for: density using a Mettler Toledo Densito 30PX, specific conductance (SC) using an Orion 013005MD electrode, pH using an Orion ROSS Sure-Flow electrode, oxidation reduction potential (ORP) using an Orion Redox/ORP electrode, dissolved oxygen (DO) using a Hach Luminescent DO sensor, and temperature was read from the SC electrode. Concentration ranges of ammonia, ammonium, phosphate, and potassium were determined in the field using colorimetric test strips. Field alkalinity was determined by titration. When density and SC values stabilized over three consecutive swab runs, produced fluids were considered sufficiently representative of formation fluids. Samples were then collected, processed, and preserved where necessary for later laboratory analysis of: anions by ion chromatography [1], cations by inductively coupled plasma – atomic emission spectroscopy based on [2], alkalinity by titration [3], total dissolved solids (TDS) by gravimetry [4], dissolved inorganic carbon (DIC) by coulometry [5], total organic carbon (TOC) by combustion [6], halides by neutron activation [7, 8], carbon isotopes [9], and oxygen isotopes [9, 10].

2.3. Westbay completion and operation

After swab testing, a Westbay^{*} multilevel groundwater characterization and monitoring system was installed. The Westbay completion in VW#1 includes 28 packers that provide multiple redundant seals to hydraulically separate the 11 perforated zones (Fig. 2). Valved ports (measurement ports and pumping ports) were positioned in the completion tubing at selected depths between the packers to provide access for purposes of fluid pressure measurement, fluid sample collection, and hydraulic testing. The ports and packers are operated by wireline-deployed tools. A more detailed description of the concept and functionality of the Westbay system is available in Black et al. [11].

^{*} Mark of Schlumberger

In VW#1, corrosion-resistant stainless steel and other alloys were used in completion tubing, valved couplings, and other components of the monitored intervals from 1,447 to 2,172 m (4,747 to 7,126 ft) depth. Elastomers used in seals and inflatable packer elements were composed of Hydrogenated Nitrile Rubber (HNBR) for resistance to CO₂ exposure. The Westbay system completion was installed from May 11 to June 13, 2011. Above a depth of 1,447 m (4,747 ft), the completion tubing is 73 mm (2-7/8 in.) diameter mild steel tubing to ground surface. An external gas injection line was installed to a depth of 350 m (1,148 ft) to allow gas lift pumping of tubing fluid, and a 207 bar (3,000 psia) rated wellhead assembly was installed for pressure control of the tubing and the tubing annulus. After the Westbay tubing string was in place, a 1.124 g/cc (9.4 ppg) corrosion-inhibited synthetic NaCl completion fluid was used to fill the tubing annulus. The inhibitor contained ammonium bisulfite, isopropanol, and tribasic sodium phosphate.

After installation of the Westbay system, measurements of fluid pressure in the 11 perforated zones were taken (Fig. 2) and illustrate the different pressure regimes that are present in the Mt. Simon Sandstone (zones 2 through 9) and above the primary seal in the Ironton-Galesville Formation (zones 10 and 11). These measurements and others from non-perforated zones were used to provide documentation of packer seal performance.

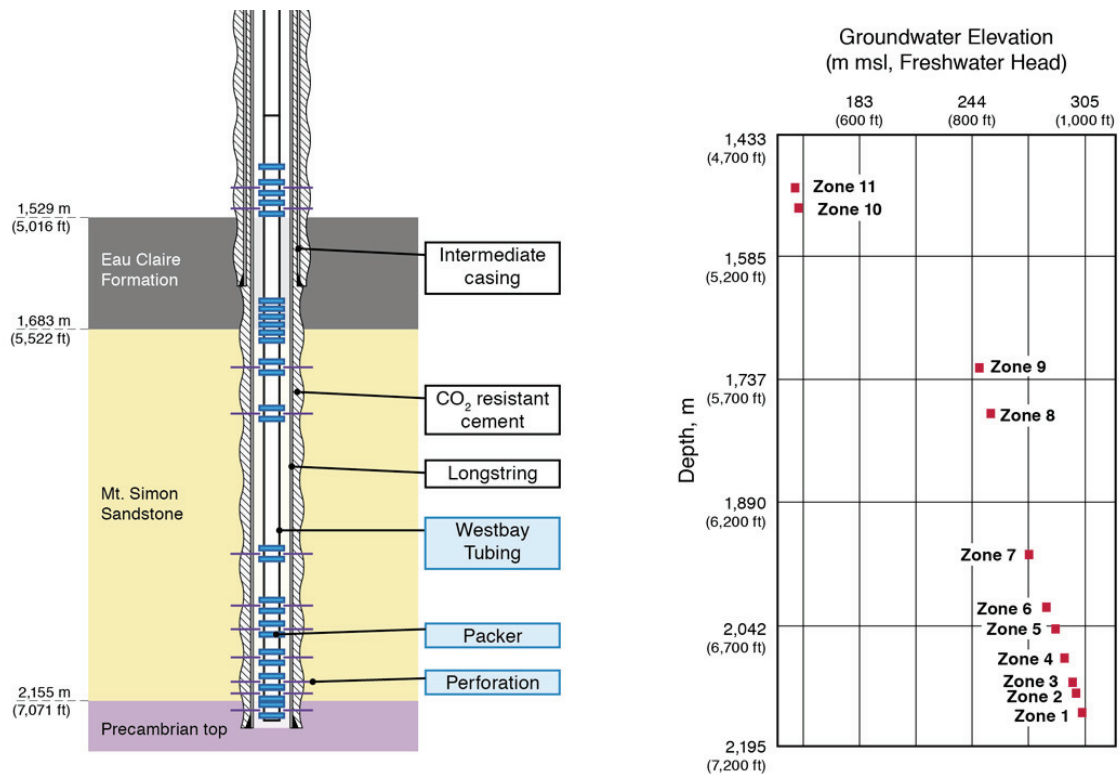


Fig. 2. Generalized diagram of IBDP VW#1 construction and completion (left) and preinjection pressure profile (right). Perforations on the left diagram correspond to the labeled zones on the right diagram. Zones 2 and 3 are in the injection horizon for the IBDP CO₂ injection well (not shown).

2.4. Westbay sampling

The Westbay system has the capability to use one or two sample bottles (Model 2471C11) each with a 1.5 L (0.40 gal) capacity for a total sample volume of up to 3.0 L (0.79 gal). Sample bottles each include valves at the top and bottom. Bottles were pre-cleaned with trisodium phosphate. Prior to each use, parts of the sampling assembly that would come in direct contact with sample were cleaned by triple rinsing with deionized water. After rinsing, bottles and valve sets were dried, weighed, assembled, evacuated to -1.9 bar (-28 psig), charged to a maximum of 2.8 bar (40 psig) with nitrogen, and then staged for deployment. For a typical deployment, two bottles were connected in series and attached at the well head to a Westbay sampler probe (Model 2582), the nitrogen was released to the atmosphere, and a vacuum of -1.9 bar (-28 psig) was applied immediately before deployment to minimize atmospheric contamination. With a two-bottle assembly, a piston was included in the bottom bottle to aid in later sample processing. After successful connection to a zone measurement port, the sampler probe valve was opened, the bottles were filled in series under formation pressure, the sampler probe valve was closed to prevent fluid loss, the sampler was disengaged from the zone port, and the bottles were retrieved to surface.

After retrieval of the bottles at the wellhead, the individual bottle valves were closed, and the bottles were detached from the sampler. The exterior was cleaned, and temperature and pressure of the bottles were obtained. Degassing often did occur within the Westbay bottle between the time of sample collection downhole and sample processing at surface. For the top bottle, a gas sample was collected if gas was present, and then the bottle was depressurized. Liquid samples were collected from the top bottle by gravity drainage and tested for field parameters. The field testing and sample processing procedures used for both Westbay sampling events was the same as swab sampling with the exception that chloride (Cl) and bromide (Br) analyses by ion chromatography were added to the Westbay sample integrity testing protocol. Available field methods for determination of Cl and Br were not sufficiently accurate to evaluate concentration similarities or differences between swab and Westbay samples. Thus, more accurate laboratory analyses were used. As swab samples were assumed to be representative of native formation fluids, comparisons of physical and compositional results from analogous Westbay samples were used to confirm Westbay sample representativeness. The remaining fluid from the top bottle was filtered through 0.45 μm filters and preserved as appropriate for later laboratory analysis as described in Section 2.2. For the bottom bottle, low pressure nitrogen gas was applied to the non-sample side of the piston to push the sample through a 0.45 μm high pressure filter assembly for samples where minimal contact with the atmosphere was desired (e.g., DIC and selected isotopes). The remaining volume was filtered and then archived under refrigeration. When a sample was determined to be unrepresentative and it was practical, additional purging was done and the zone was resampled. Two Westbay sampling events, WB1 and WB2, were conducted at VW#1 during June-July and September 2011, respectively.

2.5. Westbay pressure monitoring

After purging and sampling, a string of dedicated wireline-deployed pressure transducers was installed in the well. This allowed real-time measurement of formation fluid pressures in each of the 11 perforated intervals and fluid pressure inside the tubing. An additional pressure transducer was placed in a blank (non-perforated) zone above the Mt. Simon Sandstone at a depth of 1,670 m (5,481.5 ft) to provide ongoing confirmation of packer seal integrity. These pressure transducers were connected via a datalogger at the well head to the on-site, real-time data collection system. The transducer string is retrievable as required for maintenance, zone testing, or fluid sampling.

3. Results and Discussion

During swab testing in May 2011, 289 m³ (76,300 gal) of fluid was produced to remove non-native fluids prior to sample collection. SC and fluid density were measured in more than 245 field samples and used as primary indicators of fluid chemistry stabilization during swabbing. Figure 3 shows examples of observed SC and density values from zone 3 and 10. Zone 3 responses show removal of fluids with slightly lower density/SC and stabilization occurred after swab run 40. The zone 3 representative swab sample was collected on run 46. Zone 10 responses show an idealized curve shape. For that zone, higher density/SC fluids were removed during swabbing. Stabilization occurred after swab run 20 and the representative swab sample was collected on run 29. For most zones, SC values varied less than 1% between the final consecutive runs as stabilization was reached, and all zones were within 2%. Overall, swab samples are expected to be highly representative of native formation fluid constituents (e.g., inorganic components) that were not affected by the constant fluid agitation and air mixing that occurred during swabbing.

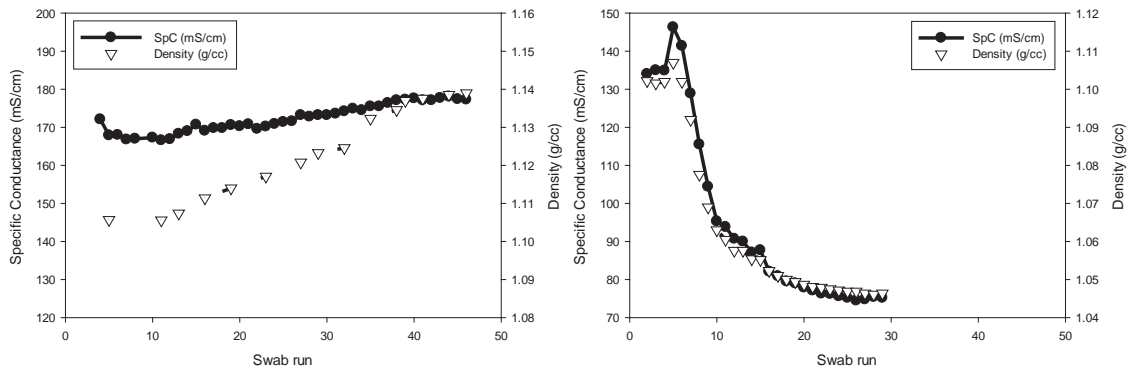


Fig. 3. Field measurements of specific conductance and density of zone 3 fluids (left) and zone 10 fluids (right) during swab testing.

Before the Westbay packers were inflated, the tubing annulus was not obstructed and completion fluids had the opportunity to migrate into the perforated zones. Because of fluid densities and relatively higher heads, zones 2 through 9 likely did not have large volumes of invasion. In contrast, it was estimated that as much as 15.9 m³ (4,200 gal) of fluid migrated into zones 10 and 11, where fluid densities and heads were relatively low in comparison to borehole conditions. Completion fluids were NaCl solutions made with local potable water. During WB1 in June/July 2011, a total of 32 m³ (8,500 gal) was purged to remove non-native fluids and 17 samples were collected from 10 zones. Purge volumes ranged from 0.80 to 7.30 m³ (210 to 1,930 gal) for individual zones.

Differences in composition between the final swab samples and completion fluids (Table 1) were used to assess sample integrity during WB1. Initially, a bromide concentration from a Westbay sample, [Br_{Westbay}], was compared to a bromide concentration from an analogous swab sample, [Br_{Swab}], and if the value of [Br_{Westbay}]/[Br_{Swab}] was 0.8 or greater, the Westbay sample was considered sufficiently representative. This provisional measure of sample integrity held true for zones 2 through 9 where concentration differences were highest between the formation brine and completion fluid, but did not hold

for zones 10 and 11 where Br concentration differences were less pronounced. Fluids that invaded zones 10 and 11 likely are a mix of completion fluids (Br concentration about 30 mg/L) and formation fluids from zones in the Mt. Simon Sandstone with high permeability, higher head and higher Br concentrations (e.g., zones 2, 3, 4). One hypothesis is that the multiple non-native fluids have mixed in zones 10 and 11 to an approximate Br concentration of 200 mg/L, which is in the same concentration range as the final swab samples (Fig. 4). This makes the $[\text{Br}_{\text{Westbay}}]/[\text{Br}_{\text{Swab}}]$ ratio unsuitable for use in zones 10 and 11. A more robust measure of sample representativeness appears to be the Cl/Br ratio. Figure 4 (right) more clearly illustrates how chemistry in zones 10 and 11 has evolved. Zones 10 and 11 remain different than original swab chemistry, but subsequent purging of those zones during WB1 and WB2 has continued to remove non-native fluids. Figure 4 (right) also seems to indicate that ratios in each zone for successive sampling events progress toward the swab value. This would be consistent with the logical deduction that after the Westbay packers were inflated to isolate individual sampling zones, repeated purging events may bring fluid compositions incrementally toward their swab values.

Table 1. Concentration ranges of selected constituents in swab samples (formation brine) and completion fluids.

	TDS (mg/L)	Cl (mg/L)	Br (mg/L)	NH ₃ (mg/L)	Density (g/cc)
Formation brine from swab samples	63,000 - 207,000	37,000 - 144,000	200 - 880	4 - 7	1.04 – 1.14
Completion fluid	164,000	96,000	30	-	1.11
Completion fluid w/ inhibitor	193,000	112,000	30	70	1.12

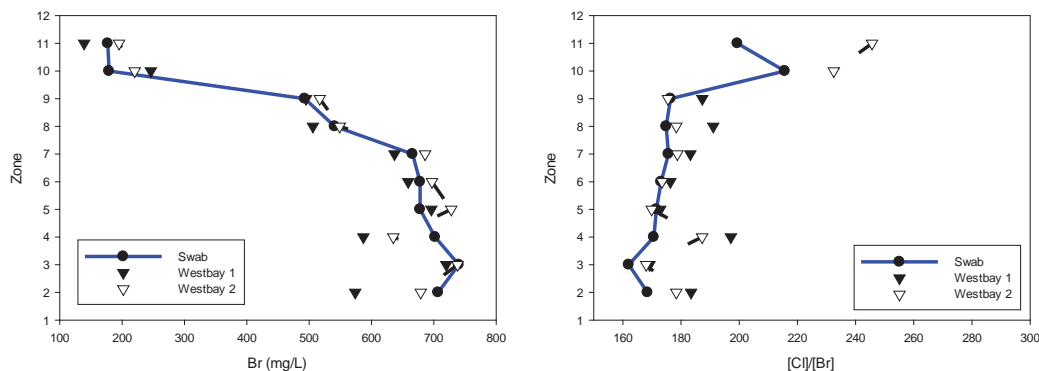


Fig. 4. Profiles for bromide concentrations (left) and chloride/bromide ratios (right). Note: Chloride/bromide ratios for zones 10 and 11 were 366 and 551, respectively, but the x-axis scale was adjusted to better show that values from zones 2 through 9 progressively approach the swab values for WB2.

During WB2 in September 2011, 22.7 m³ (6,000 gal) was purged and a total of 11 samples were collected from 10 zones. Purge volumes and resampling was reduced in zones 2 through 9 as non-native fluids had mostly been removed. Purging in zones 2 through 9 now only needs to be done immediately prior to sample collection to ‘freshen’ the volume that has been in contact with the tubing annulus and

immediate well bore region including the casing cement. Approximately four times the tubing annulus volume is now required (~40L, 10.6 gal) for routine purging.

Excluding zones 10 and 11, final swab densities are very similar to WB1 and WB2 final densities, with an average percent difference of -0.1% and 0.0%, respectively. With the exception of zone 4 (WB1), all WB1 and WB2 final densities are within +/- 0.5% of analogous swab values. Zones 10 and 11 densities were between 4-6% greater for WB1 and 1-3% greater for WB2 compared to analogous swab sample densities.

Table 2 shows the averages of primary brine constituents of the Ironton-Galesville Formation (zones 10 and 11; swab only) and the Mt. Simon Sandstone (zones 2 through 9; swab, WB1 and WB2) in comparison with average shallow (<91 m, 300 ft) groundwater chemical data also collected from the study site. Both Ironton-Galesville and Mt. Simon brines are Na+K, Ca, Cl-type brines. These and associated data establish a high-quality, site-specific data set to which future sampling results can be compared to evaluate the geochemical effects of CO₂ injection. All zone samples (initial and repeat samples) collected during swab sampling, WB1, and WB2 pass the charge balance and mass balance quality control criteria described by the American Public Health Association [12].

Table 2. Average concentrations of primary constituents in groundwater at the IBDP site. .

Constituent	Shallow Groundwater	Ironton- Galesville Formation	Mt. Simon Sandstone
SC (mS/cm)	1.5	80	170
TDS (mg/L)	1,000	65,600	190,000
Cl (mg/L)	170	36,900	120,000
Br (mg/L)	1	180	680
Alkalinity (mg/L)	380	130	80
Na (mg/L)	140	17,200	50,000
Ca (mg/L)	100	5,200	19,000
K (mg/L)	1	520	1,700
Mg (mg/L)	50	950	1,800
pH	7.2	6.9	5.9

4. Conclusions

Ensuring sample representativeness in VW#1 has been a significant undertaking due to several factors including well depth, multi-level well completion under significantly different hydraulic head conditions, and invasion of completion fluids in sampling zones.

Experience from IBDP and other projects shows multiple geochemical indicators should be used to evaluate sample representativeness in complex geochemical environments such as those influenced by well drilling, construction, and completion activity. Density, specific conductance, bromide concentrations, and chloride/bromide ratios were used at the IBDP site as indicators of sample representativeness for VW#1 sampling events.

Swab sampling provided a critical set of fluid chemistry data to which the thoroughness of zone purging could be evaluated. Without that dataset, evaluating WB1 and WB2 sample integrity would likely have been much more difficult, especially in zones 10 and 11.

Fluid compositional data and formation pressure data have been collected from VW#1. These high-quality, field-based data are essential to establish hydrochemical conditions in and above the storage reservoir prior to CO₂ injection, indicate the geochemical responses of the reservoir to CO₂ injection, provide detailed geochemical model inputs, and provide insights for on-going work at the Illinois State Geological Survey to determine the origin of Illinois Basin brines.

Acknowledgements

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