

studies have been used to predict the permeability effect of SAR on soils varying in texture, clay mineralogy, ionic exchange capacity, organic matter, and pH (Bresler et al., 1982; Quirk, 1971; Shainberg and Letey, 1984a,b; Pratt & Saurez, 1990).

Due to their distinctive cation exchange capacities (CEC), zeolites have been utilized for ion-exchange, molecular sieve and catalytic processes. Zeolites have also been shown to be effective in removing ionic substances from polluted waters (Colella, 1996; Pansini, 1996; Mumpton, 1999; Wingenfelder et al., 2005). There are approximately 40 natural (Inglezakis, 2005) and 150 synthesized (Eyde and Holmes, 2006) zeolites that have the potential for use as an ion-exchange material. Zeolites have also been shown to effectively remove Na^+ from CBNG co-produced water (Zhao et al., 2009; Ganjgunte et al., 2011).

A field demonstration and companion laboratory studies were performed to evaluate zeolite for passive remediation of CBNG co-produced water. The aim of this research was to assess the effectiveness of Bear River zeolite (BR-zeolite) in passively remediating the harmful effects of CBNG co-produced water when applied to soil. Specific objectives of this study were to evaluate impacts that HCO_3^- and chloride (Cl^-) ions had on the adsorption of Na^+ and to analyse the effect of BR zeolite on the infiltration of CBNG co-produced water through the unsaturated zone. The findings of this study can be used to further assess the feasibility of zeolite lined evaporation ponds for the management and passive remediation of CBNG co-produced waters. To the best of our knowledge, this is the first field demonstration examining the effectiveness of zeolite for this purpose.

2. Materials and methods

Zeolites are hydrated aluminosilicates of alkaline and alkaline-earth metals that are classified as analcime, chabazite, clinoptilolite, erionite, ferrierite, haulandite, laumontite, mordenite, and phillipsite minerals (Zhao et al., 2008). Bear River zeolite has a mineral composition of 85% clinoptilolite, chemical composition of 3.47% potassium (K), 1.6% Ca, and less than 0.5% of Na (U.S. Antimony United States Antimony Corporation, 2009), surface area of 2.5 km^2/kg , bulk density of 881–991 kg/m^3 , and CEC of 1.5–1.8 eq/kg . Two important properties of zeolite, as it pertains to water treatment, are surface area and CEC. The zeolite used in this study (Bear River Zeolite Company, Preston, ID) has been shown to reduce SAR from 30 to below 10 $(\text{mol}/\text{m}^3)^{1/2}$ (Zhao et al., 2008; Ganjgunte et al., 2011). Surrogate CBNG waters were synthesized by dissolving NaHCO_3 , KCl, Na_2SO_4 , NaCl, $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ and $(\text{C}_2\text{H}_5\text{O})_4\text{Si}$ in both de-ionized (type I) and city water (type II). The waters used in the field demonstration included CBNG co-produced water and city water from Sheridan, Wyoming. The CBNG co-produced water came from a nearby water discharge outfall. The SAR and major cation concentrations of the various waters used for the different studies are summarized in Table 1.

2.1. Adsorption isotherm study

An adsorption isotherm study was performed using BR zeolite with sodium bicarbonate (NaHCO_3) and sodium chloride (NaCl) solutions. The BR zeolite was crushed and sieved in order to provide a sample with a uniform particle size of 1.5–2.0 mm. Forty (40) ml solutions of NaHCO_3 and NaCl with Na^+ concentrations of 625, 1,250, 1,875, 2,500, 3,750 and 5000 mg/L as Na^+ were added to 50 ml vials containing 5 g of BR-zeolite. Each bottle was then tightly capped, placed on a mechanical horizontal rotator (Barnsted Thermolyne, Model 4152110), and rotated at 60 rpm for a period of two days (48 h) at ambient temperature ($\sim 22^\circ\text{C}$) until chemical equilibrium was reached. The supernatant solutions were then

Table 1

SAR and Na^+ , Ca^{2+} , and Mg^{2+} concentrations for the different waters used in the study.

Water type	Concentration of Cations			SAR (mol/m^3) ^{1/2}
	Na^+ (mol/m^3)	Ca^{2+} (mol/m^3)	Mg^{2+} (mol/m^3)	
Tap water in the lab, UW	1.78	0.55	0.33	1.90
City tap water in Sheridan, WY	0.63	0.14	0.04	1.47
Synthetic CBNG co-produced water (type I)	19.63	0.80	0.43	17.70
Synthetic CBNG co-produced water (type II)	17.85	0.25	0.10	30.17
CBNG co-produced water in the field study area	13.03	0.14	0.09	27.07

filtered (0.20 μm) and analyzed for Na^+ using an Inductively Coupled Plasma (ICP) Spectroscopy (Thermo Jarrell Ash, Model P300).

2.2. Adsorption kinetics study

A Na^+ adsorption kinetics study was conducted using a batch equilibration technique (Zhao et al., 2008, 2009) and four different zeolite size fractions (1.3–1.5, 1.5–1.7, 1.7–2.0, and 2.0–2.5 mm). Twenty grams of BR zeolite from each particle size fraction was added to 500 ml of synthetic CBNG water (type I) in reaction vessels and the solutions were mixed at 60 rpm using a mechanical stirrer (Phipps & Bird, Model No. 300). The vessels were sampled at 0, 30, 60, 120, 180, 300, 420, and 660 min by collecting a 1 ml aliquot of solution that was filtered through a disc filter (SFCA/PF, 0.20 μm) attached to a syringe. The samples were then diluted to 25 ml with DI water and analyzed for Na^+ , Ca^{2+} , and Mg^{2+} using ICP Spectroscopy.

2.3. Field demonstration

The field demonstration was designed to evaluate the following experimental conditions in triplicate: (1) city water without zeolite, (2) city water with zeolite, (3) CBNG water without zeolite, and (4) CBNG water with zeolite. The field demonstration site was located adjacent to the University of Wyoming Research and Extension Center in Sheridan, Wyoming. A private drilling company drilled twelve boreholes in three rows (four to a row). The boreholes in each row were located approximately 8 m from each other and the rows were spaced approximately 8 m apart. Each borehole was approximately 1.8 m deep and had a diameter slightly greater than 20 cm. Falling head permeameters were constructed using 3 m sections of 15 cm diameter schedule 40 polyvinyl chloride (PVC) pipe. The pipes were emplaced in the boreholes by hydraulically advancing each one approximately 5 cm into the soil. Since the boreholes were only 1.8 m deep this resulting in a ~ 1.2 m riser. The annulus around each pipe was filled with bentonite effectively sealing them off from the surface.

Six of the twelve boreholes were randomly selected to receive 3 kg of BR zeolite, which formed a permeable reactive barrier of approximately 8–10 cm in thickness directly above the soil. Based on the results from the adsorption isotherm study this amount of zeolite can treat approximately 180 L of CBNG co-produced water with an SAR value of 30 $(\text{mol}/\text{m}^3)^{1/2}$ reducing it to below 10 $(\text{mol}/\text{m}^3)^{1/2}$. The remaining six boreholes did not receive zeolite and served as controls. Automatic data logging pressure transducers (Level TROLL 500, In-Situ, Inc.) were calibrated and installed in the bottom of each borehole to measure water levels with time. A separate pressure transducer was attached to the outside of one of the risers to record ambient temperature and barometric pressure.

