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# Hydrological connectivity between clay settling areas and surrounding hydrological landscapes in the phosphate mining district, Peninsular Florida, USA

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Hydrological Connectivity Between Clay Settling Areas and Surrounding Hydrological  
Landscapes in the Phosphate Mining District, Peninsular Florida, **USA**

by

Kathryn E. Murphy

A thesis submitted in partial fulfillment  
of the requirements for the degree of  
Master of Science  
Department of Geology  
College of Arts and Sciences  
University of South Florida

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crack, perched aquifer

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ABSTRACT

The objective of this study was to use applied and naturally-occurring geochemical tracers to study the hydrology of clay settling areas (CSAs) and the hydrological connectivity between CSAs and surrounding hydrological landscapes. The study site is located on the Fort Meade Mine in Polk County, Florida. The surface of the CSA is covered in desiccation cracks which swell and shrink in response to wetting and drying. Bromide was used as an applied tracer to study hydrological processes in the upper part of the CSA. Bromide infiltrated rapidly and perched on an uncracked massive sublayer. Bromide concentrations attenuated in the upper part of the profile without being translated vertically down through the lower part of the profile suggesting that bromide was lost to lateral rather than to vertical downward transport. Infiltration and lateral flow were rapid suggesting that preferential flow through desiccation cracks and other macropores likely dominates flow in the upper part of the profile. Naturally-occurring dissolved constituents and stable isotopes of hydrogen and oxygen were used as naturally-occurring tracers to study the hydrological connectivity between the CSA and the surrounding hydrological landscape. The relative contributions of source waters

were determined using a two-end, mass-balance mixing model with sodium as a conservative natural tracer. On average, water samples downgradient from the CSA were ~80% rainfall/ambient water and ~20% CSA water. Discharge from the CSA to the surrounding surface water bodies and surficial aquifer occurs laterally over, through, and/or under the berms and/or vertically through the thick uncracked massive sublayer. However, the precise flowpaths from the CSA to the surrounding hydrological landscape are unclear and the fluxes remain unquantified, so the effects of CSAs on the hydrology of the surrounding and underlying hydrological landscape also remain unquantified.

## INTRODUCTION

Clay-rich deposits have low permeabilities (Manning, 1997; Fetter, 2001; Deming, 2002). Because of their low permeabilities, clay-rich deposits often confine aquifers (Fetter, 2001) and perch surface water and/or groundwater (Rains et al., 2006; Rains et al., In Review), and clay liners are often used to restrict flow down well annuli (Sanders, 1998) and into and out of solid waste disposal sites (Johnson et al., 1989). Therefore, clay-rich deposits are typically treated as homogeneous and isotropic deposits in which hydraulic properties are identical at all locations and in all directions (Dekker and Bouma, 1984). However, these assumptions are not true in clay-rich deposits with desiccation cracks (Bouma et al., 1981).

Due to interlayer water adsorption, clay-rich deposits swell when wet and shrink when dry (Tuller and Or, 2003). Where swelling and shrinking are pronounced, desiccation cracks can form in the surface and shallow subsurface. The depth of desiccation cracking depends on clay mineralogy, and is increased by factors such as wetting and drying (Vogel et al., 2005) and compaction due to grazing (Reid and Parkinson, 1984) and decreased by factors such as dispersion due to high sodium concentrations (Quirk and Schofield, 1955).

Desiccation cracks, along with other macropores associated with bioturbation such as burrows and root channels (Dekker and Ritsema, 1996), create preferential

flowpaths through which water can rapidly flow (Thomas and Phillips, 1979). This phenomenon is also known as “short-circuiting”, because water flows through the desiccation cracks and macropores rather than through the low-permeability matrix (Bouma and Dekker, 1978). Though desiccation cracks and macropores may only represent a small proportion of the total porosity of a deposit, desiccation cracks and macropores can dominate flow and transport in the shallow subsurface of many clay-rich deposits (Heppell et al., 2000; Rains et al., In Review).

Clay settling areas (CSAs) are waste products of phosphate mining in peninsular Florida. Phosphate-rich deposits cover much of peninsular Florida. Where mined, the phosphate-rich layer averages 3-4 m in thickness and is buried beneath an overburden layer that is typically 4-8 m in thickness. The phosphate-rich layer is ~50-60 % clay, ~30-40 % quartz sand, and ~2-5 % heavy minerals and other miscellaneous materials (Hawkins, 1973). Beneficiation yields phosphoric acid, gypsum, and a slurry of clay and sand that is predominantly clay with a  $d_{50}$  typically less than 0.2 microns (Hawkins, 1973). The slurry of clay and sand is ~3% solids and is disposed of in CSAs, large, above-grade reservoirs contained by rectangular, earthen berms that are ~6-15 m above grade and ~120-320 hectares in area (Lewelling and Wylie, 1993; Zang and Albarelli, 1995). Rapid consolidation and drainage ensues, with the slurry of clay and sand reaching ~18-22% solids within a few months (Zang and Albarelli, 1995). After ~5 years, a surface crust that is ~50-60% solids forms, though the deeper subsurface remains ~25% solids for many years thereafter (Ervin et al., 1997).

As of 1998, ~120,000 hectares of land had been mined in peninsular Florida, with ~40% or ~50,000 hectares covered with CSAs (Stricker, 2000). Mining continues and,

depending on economical and environmental factors, as much as ~175,000 hectares of land could be mined and as much as ~70,000 hectares of CSAs could remain when mining is complete.

The hydrology of CSAs and the subsequent effects of CSAs on water resources are poorly understood. To be sure, annual rainfall is captured by the CSAs. However, the fate of this rainfall and the original processing water still contained within the CSAs is unclear. Does it recharge the underlying surficial aquifer and flow to nearby wetlands and streams? Does it recharge the underlying Floridan aquifer? Or does it simply evaporate or enter into storage within the clay matrix and not become available for any beneficial use? This effort is part of a four-year project designed to address these and other fundamental questions of hydrological and ecological importance in Florida. Specifically, the objective of this study was to use applied and natural-occurring geochemical tracers to study the hydrology of CSAs and the hydrological connectivity between CSAs and surrounding hydrological landscapes.

## SITE DESCRIPTION

### *Location and Setting*

The study site is located on the Fort Meade Mine in Polk County, Florida (Figure 1). The CSA is ~6 m above grade and ~75 hectares in size. The CSA is ~20 years old, and the surface crust is sufficiently solid to support vehicles during the dry season. The CSA is located on un-mined land, so bottom boundary conditions are reasonably well known.

The CSA is nearly level to undulating with a slight topographic gradient from north to south (Figure 1). The southwest corner of the berm has slumped, so the topographic gradient steepens toward the southwest corner and the adjacent field. There are several closed-basin depressions that pond water seasonally. There are no surface water inflows, but there are interconnected ditches that discharge through a culvert through the east berm. The surface of the CSA is covered in desiccation cracks which swell and shrink due to wetting and drying.

The surrounding land has been mined. The mined land to the north, east, and southwest has been reclaimed, while the land to the northwest and south has not been reclaimed and remains in open pits filled with water. There was no active mining in the immediate vicinity of the CSA during the course of the study.

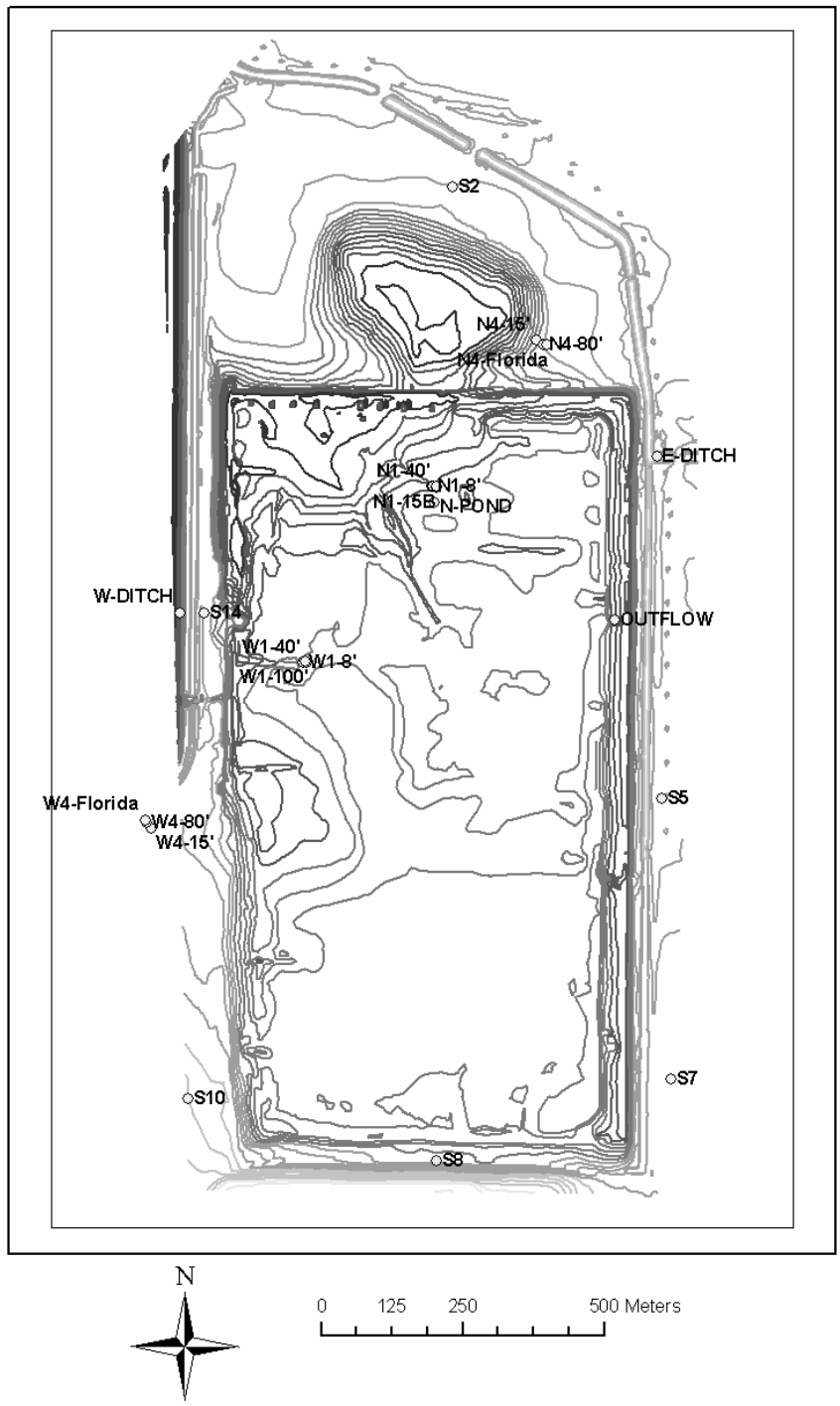


Figure 1. Topography and piezometer locations. Darker lines represent higher elevations. The CSA is the rectangular feature, and the topographic gradient of the CSA is generally from N to S.

## *Climate*

The climate at the study area is subtropical with warm, relatively dry winters and hot, relatively wet summers. Summer rainfall is due to frequent, local convective thunderstorms, while winter rainfall is due to infrequent cold fronts (Lewelling and Wylie, 1993). Mean ( $\pm$  standard deviation) annual precipitation is 135.3 cm ( $\pm$  24.5 cm), with ~65% falling during the months of May-September (Southeastern Regional Climate Center data for Bartow, Florida for calendar years 1931-2006). Annual precipitation was 154.1 cm and 100.4 cm for water years 2005 and 2006, so rainfall was normal in water year 2005 and slightly lower than normal in water year 2006 (Southeastern Regional Climate Center data for Bartow, Florida for water years 2005-2006).

## *Geology and Soils*

The central Florida phosphate mining district, where the study site is located, has three principal hydrostratigraphic units: the surficial aquifer, the intermediate aquifer system, and the Floridan aquifer system (Ervin et al., 1997). Phosphate is mined from the Bone Valley Member, a part of the Miocene-age Hawthorne Formation, located within the upper part of the intermediate aquifer system. The CSA berms are comprised of overburden from the surficial aquifer, and the CSA deposits are comprised of clay and sand from the Bone Valley Member mixed with native groundwater and processing water (Reigner and Winkler, 2001).



## *Vegetation*

The predominant vegetation is the invasive Cogon grass (*Imperata cylindrical* (L.) Raeuschel). Towards the southern end, and in topographically low areas, the predominant vegetation is the Florida willow (*Salix floridana* Chapm.).

## METHODS

### *Physical Hydrological Measurements and Analyses*

Precipitation was measured continuously and solar radiation, net radiation, soil density heat flux, temperature, humidity, and wind speed and direction were measured hourly (Campbell Scientific, Inc.). Daily reference evapotranspiration was computed using the ASCE 2005 reference ET equation (Allen et al., 2005). Actual evapotranspiration was computed by multiplying reference evapotranspiration by a daily-varying crop coefficient. The crop coefficient was computed using eddy-flux and meteorological data concurrently collected at a nearby study site with different soils but similar vegetation (D. Sumner, unpublished data). The crop coefficient for the nearby site was computed by dividing daily actual evapotranspiration computed using the data from the eddy-flux tower by daily reference evapotranspiration computed using the data from the meteorological station. A least-squares polynomial was fit to the crop coefficient v. annual water year day data and used to compute a generic daily-varying crop coefficient for use in this study.

Stage in a closed-basin depression was measured hourly with a pressure transducer and datalogger (Solinst). Piezometers were installed in the CSA and in the surficial, intermediate, and Floridan aquifers surrounding and underneath the CSA

(Figure 1). Piezometers were installed using either the direct rotary or auger methods. Piezometers had 5 cm inside diameter by 1.5 m length PVC screens and 5 cm inside diameter PVC standpipes. Time-lag errors can arise in piezometers screened in low-conductivity formations such as the CSA (Hanschke and Baird, 2001). The potential for time-lag errors was minimized during data analysis by interpreting time-series data over the course of days and weeks, which eliminated time-lags that occurred over the course of hours.

A water budget was computed for a selected closed-basin depression, hereafter called the north pond, where

$$\Delta S = P - ET + \Delta SW + \Delta GW$$

and where  $\Delta S$  is the change in storage (i.e., the stage of north pond),  $P$  is precipitation,  $ET$  is evapotranspiration,  $\Delta SW$  is net surface water inflow, and  $\Delta GW$  is net groundwater inflow. There were no surface water inflows or outflows so  $\Delta SW$  was assumed to be negligible, and the simplified water budget was resolved in terms of  $\Delta GW$ . Therefore, the simplified water budget was

$$\Delta GW = \Delta S - P + ET$$

and was resolved on daily time steps during a portion of the wet season to determine the relative contributions of groundwater inflow and outflow to observed changes in stage.

#### *Tracer Application and Data Collection*

Bromide was used as an applied tracer to study hydrological processes in the upper part of the CSA. Ten infiltration rings 60 cm in diameter and 10 cm in height were

placed 5 m apart perpendicular to the surface slope on the northern part of the CSA. Five infiltration rings were randomly assigned to be controls while five infiltration rings were randomly assigned to be treatments. Five L of 60 g/L LiBr solution was applied with a shower-head watering can to the surface of the treatment infiltration rings. All water immediately infiltrated and there was no ponding in any of the infiltration rings.

Porewaters were collected from core samples. Cores were obtained by augering with an open-barrel auger to predetermined depths, extracting the core material from the open-barrel auger, and placing the core material in wide-mouthed 300 mL HDPE sample bottles. Core samples ranged from approximately 100-300 g. Core samples were collected at 0-5 cm, 5-15 cm, 15-25 cm, 25-35 cm, 35-45 cm, 45-55 cm, and 95-105 cm depths. Core samples from control infiltration rings were obtained on day 0 (June 28) right after application of the deionized water. Core samples from treatment rings were obtained on day 1 (June 29), week 1 (July 5), month 1 (July 26), and month 3 (September 29). After core samples were collected, boreholes were backfilled with native materials to avoid down-borehole contamination.

Porewaters were extracted from the core samples using a hydraulic sediment squeezer (Manheim et al., 1994). Approximately 30-50 g well-mixed subsamples were placed in capsules and subjected to pressures of approximately 500-1500 psi, depending on clay content. Porewaters were filtered through 2.7  $\mu\text{m}$  hardened low ash filters (Whatman). Porewaters were collected in 10 mL syringes and transferred to 30 mL HDPE sample bottles. Porewater samples ranged from 1-10 mL.

### *Natural Geochemical Tracer Data Collection*

Naturally-occurring dissolved constituents and stable isotopes of hydrogen and oxygen were used as natural tracers to study the hydrological connectivity between the CSA and the surrounding hydrological landscape. Rainfall samples were collected periodically, and surface water and groundwater samples were collected in the dry season (i.e., April 7, 2006) and wet season (i.e., September 4, 2007). Samples were collected from ponds and ditches on and around the CSA, from piezometers in the CSA, and from piezometers in the surficial, intermediate, and Floridan aquifers around and underneath the CSA (Figure 1). Some samples were collected far from and/or upgradient of the CSA. These samples were considered to represent ambient conditions. Since the topographic gradient is generally north to south, these samples were largely collected north of the CSA. Other samples were collected close to and/or downgradient of the CSA. These samples were considered to potentially represent mixes of ambient conditions and CSA conditions. Again, since the topographic gradient is generally north to south, these samples were largely collected west, south, or east of the CSA. In both the dry season and the wet season, two rainfall samples and 23 surface water and groundwater samples were collected and analyzed for dissolved constituents and 23 surface water and groundwater samples were collected and analyzed for stable isotopes.

Samples were pumped through 0.45  $\mu\text{m}$  in-line filters (Whatman) directly into either 60 mL HDPE sample bottles for dissolved constituent analyses or 30 mL HDPE sample bottles for stable isotope analyses. When possible, piezometers were purged

approximately ~3 volumes before samples were collected. Stable isotope sample bottles were filled completely with negligible head space and sealed with parafilm to prevent air contamination. Anion sample bottles were pre-acidified with 1 mL of nitric acid.

### *Laboratory Analyses*

Temperature, pH, and electrical conductivity were measured in the field (YSI). Major cation and anion analyses were conducted at the University of South Florida Center for Water Analysis. Major cation concentrations were determined by inductively coupled plasma-emission spectroscopy (ICP-OES) following the EPA 200 method (Clesceri et al. 1998), and major anion concentrations were determined by ion chromatography following the EPA 300 method (Clesceri et al. 1998). Bicarbonate concentrations were back-calculated by assuming all other cation and anions had been measured and that bicarbonate accounted for the entire missing charge in charge balance error analysis. Stable isotope analyses were conducted at the UC Davis Department of Geology Stable Isotope Laboratory. Deuterium analyses were performed using the hydrogen equilibration technique (Coplen et al. 1991), while oxygen-18 analyses were performed using the carbon dioxide equilibration technique (Epstein and Mayeda 1953). Deuterium and oxygen-18 are reported in the conventional, delta notation ( $\delta$ ) where

$$\delta = \left( \frac{R_{sample}}{R_{standard}} - 1 \right) * 1000$$

and where R is the ratio D/H or  $^{18}\text{O}/^{16}\text{O}$  for deuterium and oxygen-18, respectively (Craig 1961). The resulting sample values of  $\delta\text{D}$  and  $\delta^{18}\text{O}$  are reported in per mil (‰)

deviation relative to Vienna Standard Mean Ocean Water (VSMOW) and, by convention the  $\delta D$  and  $\delta^{18}O$  of VSMOW are set at 0 ‰ VSMOW (Gonfiantini 1978).

### *Mass-Balance Mixing Modeling*

The relative contributions of rainfall, ambient surface water and surficial groundwater (hereafter referred to as ambient water), and CSA groundwater (hereafter referred to as CSA water) to surface water and surficial groundwater downgradient of the CSA (hereafter referred to as downgradient water) were determined using a two-end, mass-balance mixing model with sodium as a conservative natural tracer. The mass-balance mixing model was run in both dry and wet seasons. Rainfall and ambient water were similar, so rainfall and ambient water were considered a single end member. End members were assigned mean sodium concentrations of 0.83 mg/L for rainfall/ambient water, and 36.27 mg/L for CSA water. The mass-balance mixing model was

$$\begin{aligned}Na_{DG} &= f_{RA}Na_{RA} + f_{CSA}Na_{CSA} \\f_{RA} + f_{CSA} &= 1\end{aligned}$$

where  $Na$  are sodium concentration,  $f$  are proportions that sum to one, and the subscripts ‘DG’, ‘RA’, and ‘CSA’ refer to downgradient water, rainfall/ambient water, and CSA water respectively. The primary assumption of the two-end, mass-balance mixing model was that a given sample was an instantaneous mix of the two end members.

## RESULTS

### *Applied Tracer*

Rain fell between the initial tracer application and the first sampling effort, and continued to fall periodically between each additional sampling effort (Figure 2). Mean ( $\pm$  standard deviation) bromide concentrations in the control infiltration rings were 0.0019 ( $\pm$  0.0023) g/L, while bromide concentrations in the treatment infiltration rings were 2.10 ( $\pm$  3.29) g/L (Appendix I). Maximum and minimum bromide concentrations in the treatment infiltration rings were found on day 1 and month 3, respectively. Vertical profiles show transport to  $\sim$ 0.5 m depth was substantial by day 1, but that transport to  $\sim$ 1 m depth was negligible even by month 3 (Figure 3). Bromide concentrations attenuated in the upper part of the profile without being translated vertically down through the lower part of the profile suggesting that bromide was lost to lateral rather than to vertical downward flow.

### *Pond Water Budget*

The north pond responded slowly to early wet season rainfall (Figure 4). Rain fell throughout the dry season and into the wet season without any surface water accumulation within the north pond indicating that rainfall was infiltrating and



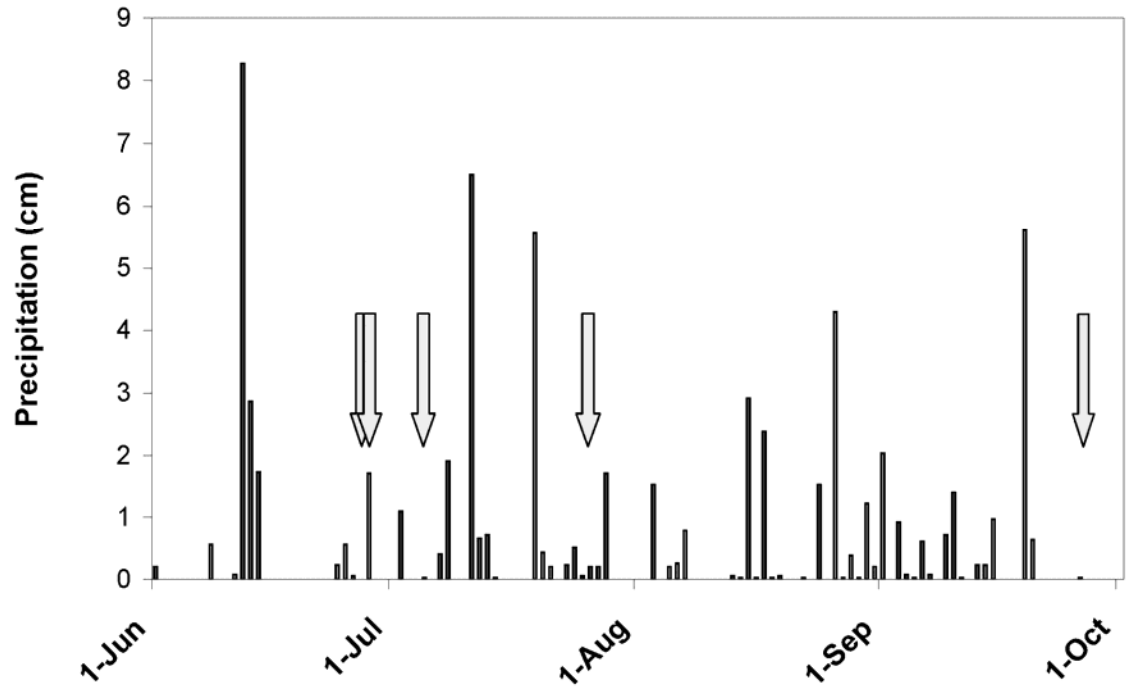


Figure 2. Rainfall in cm/d at the CSA immediately before, during, and after the tracer application. Arrows indicate core sampling efforts on day 0, day 1, week 1, month 1, and month 3, respectively.

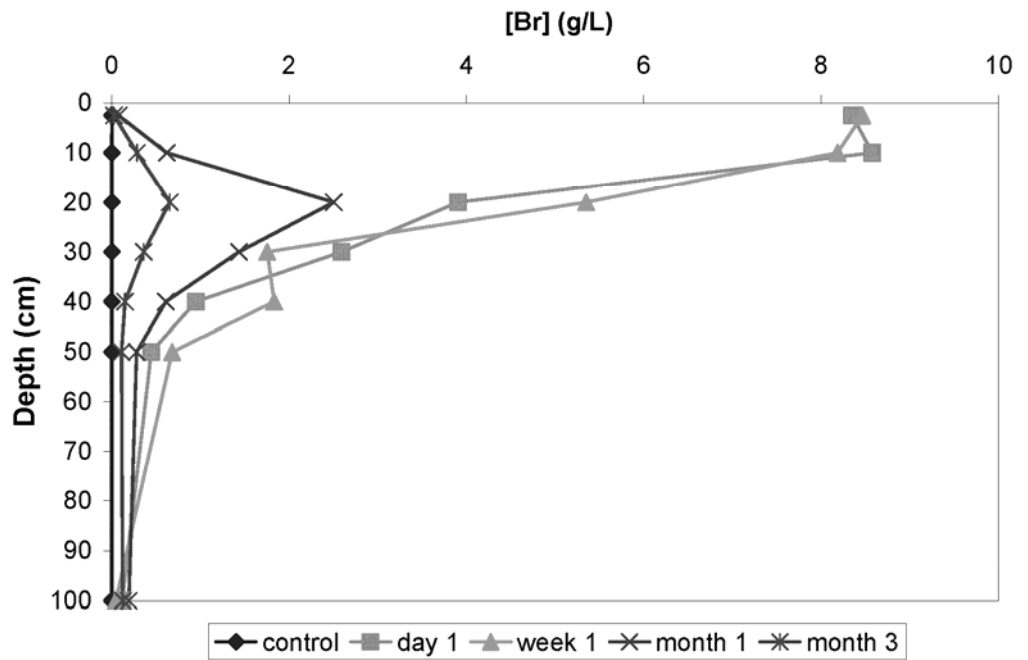


Figure 3. Average bromide concentrations in g/L v. depth in the 5 control and 5 treatment infiltration rings. The 5 control infiltration rings were sampled on day 0, and the 5 treatment sites were sampled on day 1, week1, month 1, and month 3.

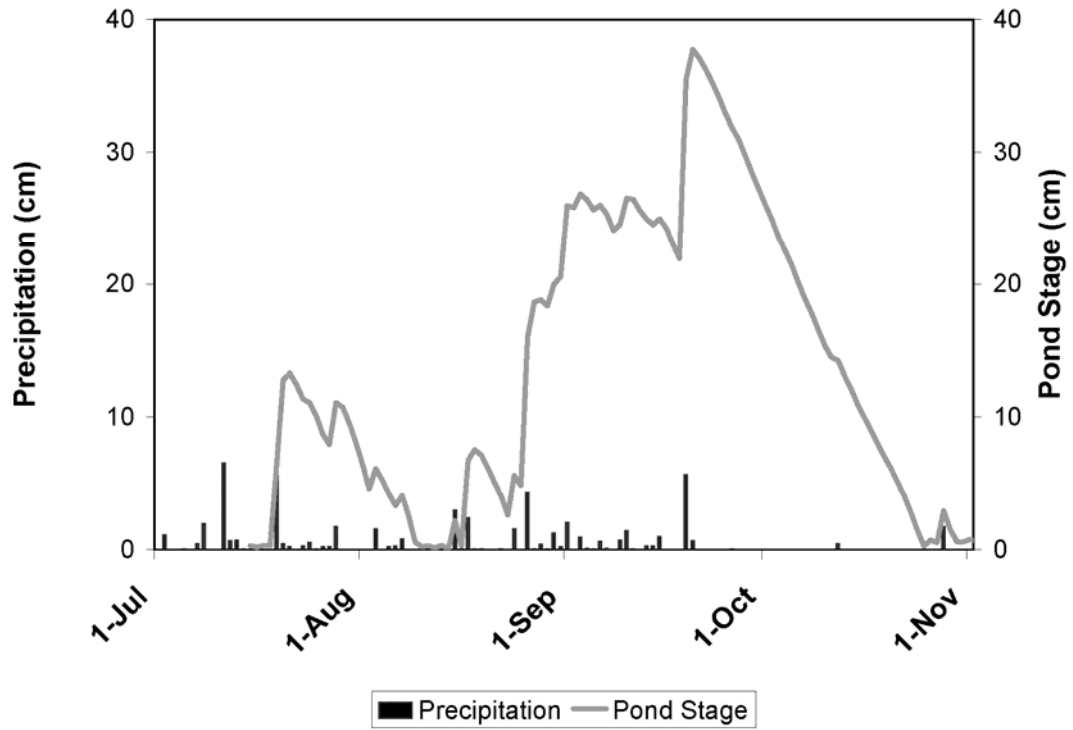


Figure 4. Precipitation in cm/d and stage of the north pond in cm immediately before and during the entire period of inundation.

augmenting soil moisture. On July 15, stage in the north pond rose 0.27 cm even though no rain fell on July 15<sup>th</sup>, and only 0.025 cm fell July 14<sup>th</sup>. Thereafter, stage in the north pond typically rose higher than could be expected from direct precipitation alone. In total, surface water was present in the north pond from July 15<sup>th</sup>-November 7<sup>th</sup>. During this time, water levels in the piezometers within the CSA remained well-below the ground surface. Therefore, this water was perched above free groundwater in the lower portion of the CSA.

There were no surface water inflows or outflows, and overland flow was never observed even during the rapid water applications to the control and treatment infiltration rings. Therefore, surface water inflows beyond some localized overland flow were believed negligible. If surface water inflow is neglected, then net groundwater inflow ranged from -3.9-12.0 cm/day (Figure 5). In October, when rainfall was negligible, net groundwater inflow was ~0.9 cm/day. Evapotranspiration was ~0.5 cm/day, so net groundwater inflow even during this period of steady drawdown was much larger than could be explained by error in the evapotranspiration estimate alone.

### *Natural Tracers*

Rainfall, ambient water, downgradient water, and CSA water had different geochemical signatures (Table 1; Figure 6; Appendix II). Rainfall and ambient water had relatively low concentrations of all dissolved constituents and were therefore combined in Table 1 and in the subsequent mass-balance mixing analyses. Dissolved constituent concentrations and isotopic ratios of the downgradient water were intermediate between

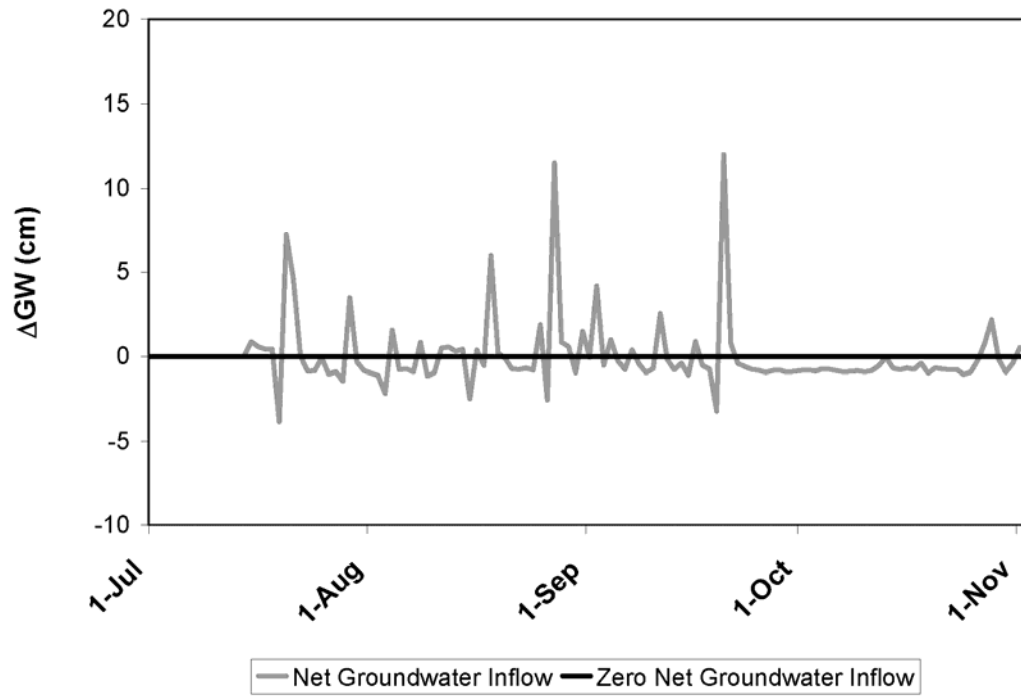


Figure 5. Net groundwater inflow to the north pond in cm/d immediately before and during the entire period of inundation.

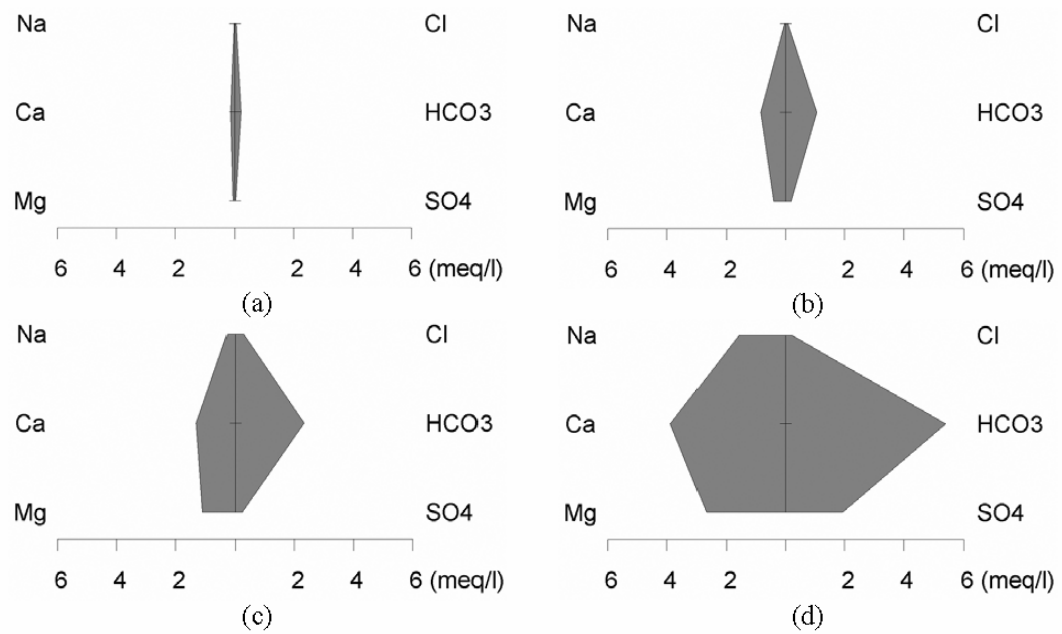


Figure 6. Stiff diagrams of the four types of water: (a) rainfall; (b) ambient water; (c) downgradient water; and (d) CSA water . Only the most common dissolved constituents are used, and concentrations are in meq/L.

Table 1. Physical and chemical properties of rainfall/ambient water, CSA water, and downgradient water. Values are means ( $\pm$  standard deviations).

Constituent	Rainfall/ Ambient (n=5)	Downgradient (n=22)	CSA Water (n=6)
pH	6.38 ( $\pm$ 0.29)	6.18 ( $\pm$ 0.75)	6.70 ( $\pm$ 0.19)
EC ( $\mu$ s cm <sup>-1</sup> )	152 ( $\pm$ 58)	318 ( $\pm$ 297)	752 ( $\pm$ 71)
T ( $^{\circ}$ C)	27.0 ( $\pm$ 5.5)	23.8 ( $\pm$ 3.9)	23.4 ( $\pm$ 2.7)
Na (mg L <sup>-1</sup> )	0.83 ( $\pm$ 0.14)	6.45 ( $\pm$ 4.80)	36.27 ( $\pm$ 9.65)
K (mg L <sup>-1</sup> )	0.84 ( $\pm$ 0.54)	1.05 ( $\pm$ 0.75)	1.25 ( $\pm$ 0.47)
Ca (mg L <sup>-1</sup> )	14.20 ( $\pm$ 7.07)	27.59 ( $\pm$ 29.49)	77.87 ( $\pm$ 8.97)
Mg (mg L <sup>-1</sup> )	4.12 ( $\pm$ 2.88)	13.96 ( $\pm$ 15.75)	32.58 ( $\pm$ 4.79)
Fe (mg L <sup>-1</sup> )	1.40 ( $\pm$ 2.22)	5.42 ( $\pm$ 7.68)	6.70 ( $\pm$ 7.11)
Mn (mg L <sup>-1</sup> )	0.03 ( $\pm$ 0.04)	0.03 ( $\pm$ 0.04)	0.19 ( $\pm$ 0.04)
Sr (mg L <sup>-1</sup> )	0.04 ( $\pm$ 0.03)	0.04 ( $\pm$ 0.05)	0.30 ( $\pm$ 0.07)
F (mg L <sup>-1</sup> )	0.45 ( $\pm$ 0.56)	0.64 ( $\pm$ 0.89)	1.94 ( $\pm$ 0.26)
Cl (mg L <sup>-1</sup> )	2.14 ( $\pm$ 0.70)	10.14 ( $\pm$ 6.87)	7.145 ( $\pm$ 1.72)
HCO <sub>3</sub> (mg L <sup>-1</sup> )	53.91 ( $\pm$ 25.54)	151.02 ( $\pm$ 183.48)	330.76 ( $\pm$ 87.35)
SO <sub>4</sub> (mg L <sup>-1</sup> )	7.11 ( $\pm$ 8.60)	10.70 ( $\pm$ 10.56)	91.89 ( $\pm$ 74.20)
SiO <sub>2</sub> (mg L <sup>-1</sup> )	2.20 ( $\pm$ 1.59)	4.39 ( $\pm$ 3.45)	4.97 ( $\pm$ 1.09)
<sup>18</sup> O (‰ VSMOW)	-3.9 ( $\pm$ 0.6)	-2.7 ( $\pm$ 0.8)	-2.4 ( $\pm$ 0.5)
D/H (‰ VSMOW)	-21.3 ( $\pm$ 4.5)	-13.8 ( $\pm$ 4.6)	-11.3 ( $\pm$ 2.5)

dissolved constituent concentrations and isotopic ratios of rainfall/ambient water and CSA water. This suggests that downgradient water is a mix of rainfall/ambient water and CSA water.

### *Mass-Balance Mixing Modeling*

Sodium best delineates rainfall/ambient water, downgradient water, and CSA water, with downgradient water having sodium concentrations that were intermediate between rainfall/ambient water and CSA water (Figure 7). The mean ( $\pm$  standard deviation) contribution of rainfall/ambient water to downgradient water was 0.81 ( $\pm$  0.13), while the mean ( $\pm$  standard deviation) contribution of CSA water to downgradient water was 0.19 ( $\pm$  0.13) (Table 2; Figure 8; Appendix III). Evidence of CSA water was found in surface water and in the surficial aquifer around the perimeter of the CSA and in the surficial aquifer underneath the CSA.



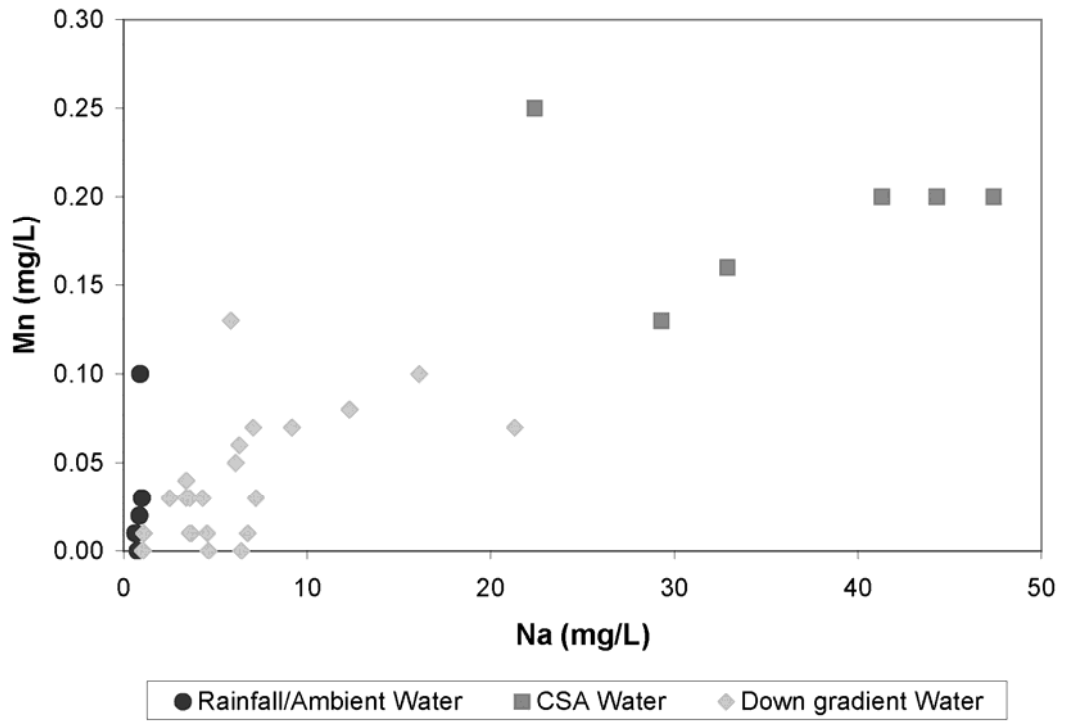


Figure 7. Scatterplot of sodium v. manganese concentration in mg/L indicating that downgradient water is a mix of rainfall/ambient water and CSA water.

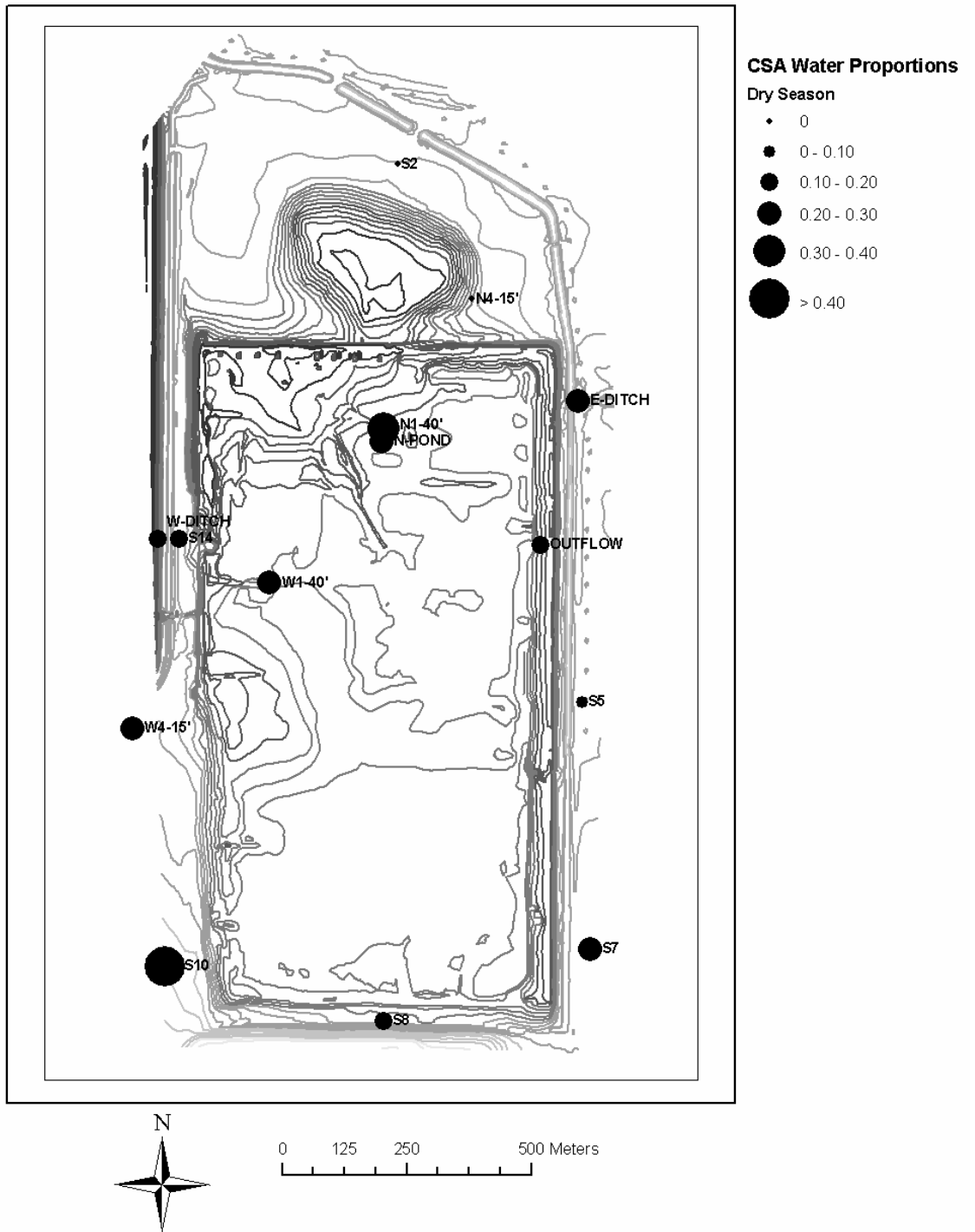


Figure 8a. Postplot of the proportional contribution of CSA water to downgradient water in dry season. The size of the circles is proportional to the contribution of CSA water to downgradient water.

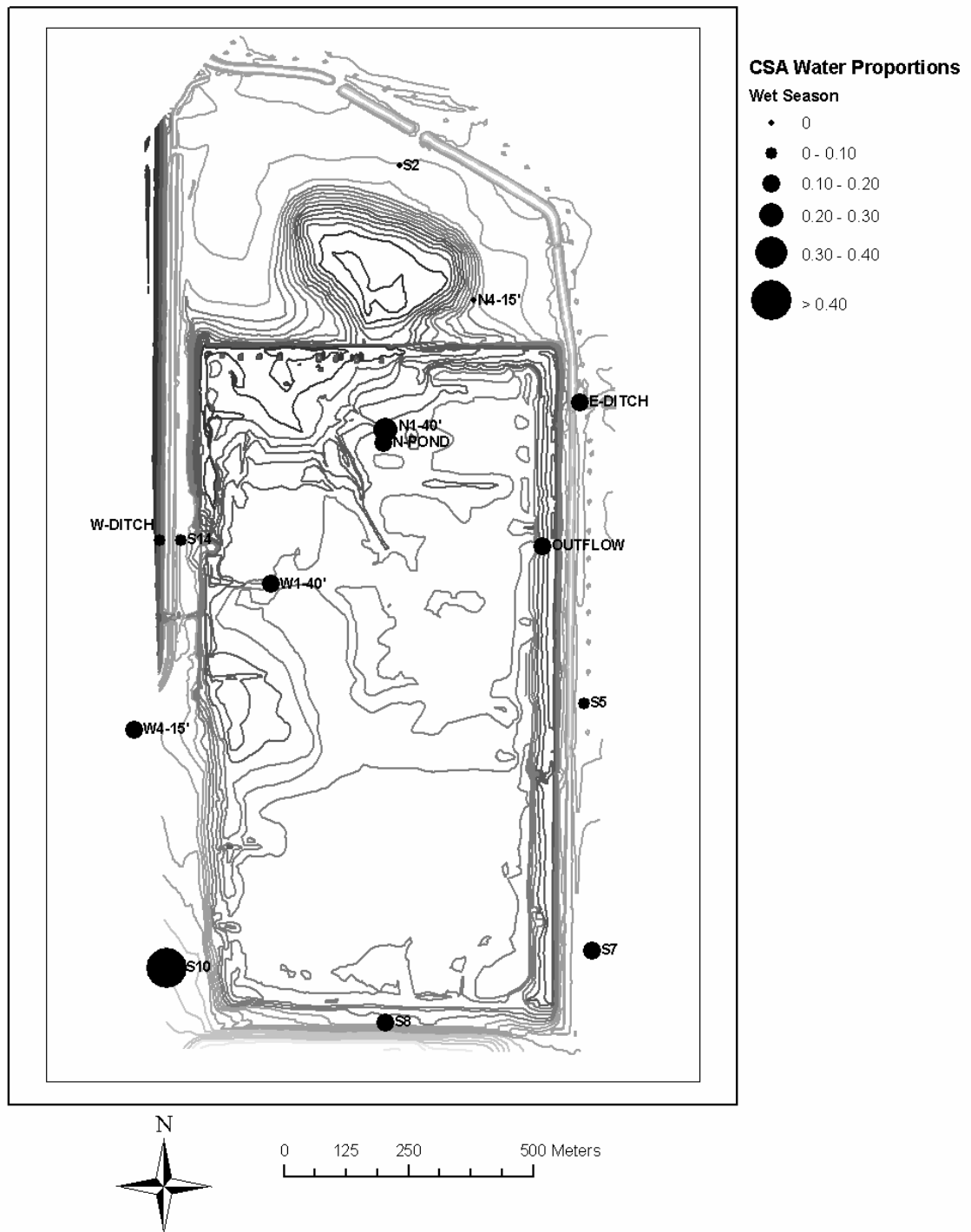


Figure 8b. Postplot of the proportional contribution of CSA water to downgradient water in wet season. The size of the circles is proportional to the contribution of CSA water to downgradient water.

Table 2. Proportion of rainfall/ambient water and CSA water in downgradient water as determined by mass-balance mixing analyses using sodium as a conservative, natural tracer.

<b>Time Period</b>	<b>Rainfall/Ambient Proportion</b>	<b>CSA Water Proportion</b>
Dry Season	0.75 ( $\pm$ 0.13)	0.25 ( $\pm$ 0.13)
Wet Season	0.84 ( $\pm$ 0.12)	0.16 ( $\pm$ 0.12)
Annual	0.81 ( $\pm$ 0.13)	0.19 ( $\pm$ 0.13)

## DISCUSSION

Bromide infiltrated rapidly through the upper ~0.5 m but either did not infiltrate or infiltrated much more slowly below ~0.5 m. With time, bromide concentrations attenuated without being measurably translated down the profile. Uptake by plants might have accounted for some but not all of the observed bromide loss (Whitmer et al., 2000). The remainder was likely lost to lateral transport. Lateral flow was evident in the water budget for the north pond, which had substantial amounts of groundwater inflow and/or outflow throughout the period of inundation.

The hydraulic conductivity of clay typically ranges from  $10^{-5}$ - $10^{-7}$  m/d (Morris and Johnson, 1967; Davis, 1969). These values were confirmed by slug tests (A. Cirra, unpublished data). Therefore, flow through the clay matrix alone cannot explain the apparent flow rates. Instead, preferential flow through desiccation cracks and other macropores likely dominates flow and transport in the upper ~0.5 m of the CSA. Rainfall infiltrates rapidly through the cracked clay surface layer, and the subsurface water perches on the uncracked massive clay sublayer below and flows laterally through the cracked clay surface layer across the CSA.

The geochemical signature of CSA water was evident in the downgradient water both around the perimeter and underneath the CSA throughout the year. The relative proportions of CSA water in the downgradient water were highest in the dry season and

lowest in the wet season, perhaps due to dilution by the additional rainfall. However, the precise flowpaths and fluxes from the CSA to the surrounding hydrological landscape are unclear.

CSA water may discharge laterally over, through, or under the berms. The CSA has a slight topographic gradient from north to south, though smaller areas have slight topographic gradients to the west and east. Therefore, some of the perched subsurface water flows laterally toward the west, south, and east berms. Some of this water discharges to a system of ditches that discharge from the CSA to the perimeter ditch through a culvert through the east berm. However, much of this water remains in the shallow subsurface and may discharge from the CSA to the surrounding surface water bodies and surficial aquifer over, through, and/or under the berms. This may be particularly true in the southwest corner where the berm has slumped and the topographic gradient steepens toward the southwest corner and the adjacent field.

CSA water also may discharge vertically through the bottom of the CSA. CSAs are the highest topographic features in the region. Therefore, water stored in the CSAs is stored well-above the water in the surficial aquifer. Therefore, downward driving forces are high and may be high enough to drive water through the thick uncracked massive clay sublayer. However, it may also be true that the CSA water in the surficial aquifer below the CSA flows laterally from where it accumulates around the perimeter of the CSA to the surficial underneath the CSA, and/or down the annuli of the surficial, intermediate, and Floridan piezometers drilled through the CSA.

Closed-basin depressions form on CSAs because the mixed clay and sand deposits settle differentially and have low hydraulic conductivities. Lewelling and Wylie

(1993) suggested that surface water storage in these closed-basin depressions reduces runoff from CSAs. Our results indicate that the hydrology of CSAs is more complex, with rapid infiltration, storage and flow in a perched subsurface flow system, and subsurface flow flowing through the closed-basin depressions. Therefore, the closed-basin depressions and cracked clay surface layer are assumed to be part of the same integrated surface water and perched subsurface water flow systems. Regardless, surface and subsurface water are temporarily stored above the uncracked massive sublayer and must either flow laterally over, through, or under the berms or vertically through the thick uncracked massive sublayer before discharging to the surrounding surface water bodies or to the surrounding and underlying surficial aquifer.

## CONCLUSIONS

In this study, we used applied and naturally-occurring geochemical tracers to study the hydrology of CSAs and the hydrological connectivity between CSAs and the surrounding hydrological landscapes. The results of this study indicate that older CSAs with well-developed cracked surface layers may have integrated surface water and perched subsurface water flow systems, and that water flows from older CSAs with well-developed cracked surface layers into the surrounding and underlying hydrological landscapes laterally over, through, or under the berms and/or vertically through the thick uncracked massive sublayer. However, the fluxes remain unquantified, so the effects of CSAs on the hydrology of the surrounding and underlying hydrological landscape also remain unquantified.



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## LIST OF APPENDICES

Appendix I. List of all bromide concentrations for all control and treatment samples in g/L.

6/28/2006 (day 0)					
site	6	7	8	9	10
depth (cm)					
0-5	0.00	0.01	0.01	0.00	0.00
15-25	0.00	0.00	0.00	0.00	0.00
15-25	0.00	0.00	0.00	0.00	0.00
25-35	0.00	0.00	0.00	0.00	0.00
35-45	0.00	0.00	0.00	0.00	0.00
45-55	0.00	0.00	0.01	0.00	0.00
95-105	0.00	0.00	0.00	0.00	0.00
6/29/2006 (day 1)					
site	1	2	3	4	5
depth (cm)					
0-5	14.94	7.57	9.75	5.39	4.11
15-25	10.39	6.68	14.50	4.58	6.73
15-25	1.98	4.80	1.71	5.48	5.57
25-35	0.07	2.43	0.14	5.48	4.85
35-45	0.08	1.98	0.02	0.82	1.85
45-55	0.03	1.38	0.11	0.09	0.63
95-105	0.05	0.16	0.01	0.15	0.22
7/5/2006 (week 1)					
site	1	2	3	4	5
depth (cm)					
0-5	6.75	10.23	6.44	11.73	7.18
15-25	9.82	10.22	6.44	5.03	9.41
15-25	6.27	6.42	3.12	5.59	xxx
25-35	1.53	3.74	0.59	1.16	xxx
35-45	0.32	2.63	0.43	0.61	5.18
45-55	0.05	1.75	0.34	0.18	1.10
95-105	0.06	0.03	0.04	0.01	0.10
7/26/2006 (month 1)					
site	1	2	3	4	5
depth (cm)					
0-5	0.02	0.09	0.10	0.06	0.12
15-25	0.54	0.10	1.92	0.02	0.53
15-25	1.98	0.66	5.38	0.04	4.47
25-35	1.35	1.55	2.04	0.27	1.98
35-45	0.68	0.54	0.63	xxx	0.59
45-55	0.16	0.53	0.02	0.17	0.53
95-105	0.05	0.13	xxx	0.01	0.58
9/29/2006 (month 3)					
site	1	2	3	4	5
depth (cm)					
0-5	0.06	0.01	0.03	0.01	0.03
15-25	0.83	0.04	0.41	0.01	0.14
15-25	2.10	0.06	0.78	0.00	0.33
25-35	1.21	0.04	0.17	0.02	0.37
35-45	0.40	0.04	0.04	0.01	0.26
45-55	0.17	0.03	0.05	0.02	0.29
95-105	0.17	0.07	0.07	0.03	0.28

Appendix IIa. Dry season values for all constituents for all samples.

Sample ID	pH	EC µS/cm	T °C	Na mg L <sup>-1</sup>	K mg L <sup>-1</sup>	Ca mg L <sup>-1</sup>	Mg mg L <sup>-1</sup>	Fe mg L <sup>-1</sup>	Mn mg L <sup>-1</sup>	Sr mg L <sup>-1</sup>	F mg L <sup>-1</sup>	Cl mg L <sup>-1</sup>	HCO3 mg L <sup>-1</sup>	SO4 mg L <sup>-1</sup>	SiO2 mg L <sup>-1</sup>	<sup>18</sup> O/ <sup>16</sup> O D/H (% VSMOW)
Average Rainfall	-	-	-	0.64	1.33	3.09	0.83	0.04	0.01	0	0.02	1.38	12.43	1.09	0.07	-
E- Ditch	6.22	193	19.3	7.05	0.61	16.9	9.53	0.31	0.07	0.03	0.58	11.29	75.12	18.19	2.15	-2.07
N1-100	6.1	121	21.7	13.2	1.1	33	16.2	0.21	0.03	0.08	1.37	9	165.62	26.46	8.7	-1.8
N1-15B	6.79	663	21.3	32.9	0.95	66.1	27.4	2.19	0.16	0.22	1.6	9.12	360.13	40.96	5.12	-1.84
N1-40	7.45	356	21.7	3.68	0.12	9.46	4.46	2.71	0.01	0.01	0.08	2.97	19.67	33.1	3.13	-3.41
N1-8	6.88	732	20.9	22.4	0.64	86.9	37.5	0.1	0.25	0.34	2.23	6.44	276.49	172.96	4.31	-2.95
N4-15	6.77	167	22.8	0.76	0.66	19.2	7.01	0.02	0	0.06	0.73	2.95	74.87	11.45	3.65	-4.52
N4-80	7.6	256	22.4	3.83	0.47	24.4	14.4	0	0	0.06	1.03	5.49	142.25	2.03	8.33	-3.38
N4-FL	7.69	216	23.5	11.7	10.8	15.1	2.65	0.01	0	0.19	2.26	10.96	51.7	23.24	9.87	-1.55
N-Pond	7.31	490	19.4	7.76	2.01	56.2	31.7	0.21	0.08	0.14	2.98	10.09	326.03	1.49	1.03	1.06
Outflow	7.11	399	17.1	4.55	1.09	51.6	26.1	0	0.01	0.15	2.2	6.55	269.31	11.43	1.55	-2.13
S-10	6.53	925	20.7	16.1	1.96	103	57.3	10.22	0.1	0	0.97	30.5	608.67	1.97	5.41	-2.03
S-14	5.58	78	21.2	3.4	0.21	4.69	0.75	2.05	0.03	0.01	0	10.62	9.36	3.15	1.9	-2.75
S-2	6.15	82	21.9	0.86	0.02	13.1	2.67	0.46	0.02	0.04	0.09	2.74	48.86	2.25	1.59	-3.14
S-5	5.43	37	21	1.04	0	0.08	1.18	0.27	0	0	0.07	14.81	0	5.59	2.07	-3.95
S-7	6.11	208	19.9	9.17	0.58	12.5	6.35	16.59	0.07	0.04	0.23	12.26	98.31	8.94	9.49	-2.18
S-8	5.29	113	22.5	4.62	0.08	1.88	2.43	8.89	0	0	0.05	5.94	0.44	30.41	2.37	-3.29
W1-100	7.36	359	21.7	11.2	0.86	34	18.9	0.19	0.01	0.06	1.27	9.52	190.17	15.21	15.37	-2.09
W1-40	5.96	84	21.6	6.75	0.4	6.59	2.63	0.56	0.01	0.01	0.4	12.24	20.68	7.62	4.64	-1.81
W1-8	6.87	692	20.8	29.3	0.89	78.1	30.5	0.3	0.13	0.23	1.8	8.6	190.27	0	5.69	-2.26
W4-15	6.48	472	19.9	6.3	1.54	47.5	30.6	1.23	0.06	0.01	0.8	11.02	296.06	0.9	4.25	-3.6
W4-80	7.18	321	20.1	32.2	1.79	19.9	7.67	0.14	0	0.03	0.82	6.06	128.44	36.29	2.89	-2.45
W4-FL	6.74	285	22.9	11	0.76	32.8	7.51	0.19	0	0.03	0.92	7.99	121.03	24.06	0.68	1.33
W-Ditch	6.4	281	19.6	5.83	0.33	33	12.2	4.95	0.13	0.12	0.53	9.65	144.63	20.19	1.19	-1.26

Appendix IIb. Wet season values for all constituents for all samples.

Sample ID	pH	EC uS/cm	T °C	Na mg L <sup>-1</sup>	K mg L <sup>-1</sup>	Ca mg L <sup>-1</sup>	Mg mg L <sup>-1</sup>	Fe mg L <sup>-1</sup>	Mn mg L <sup>-1</sup>	Sr mg L <sup>-1</sup>	F mg L <sup>-1</sup>	Cl mg L <sup>-1</sup>	HCO3 mg L <sup>-1</sup>	SO4 mg L <sup>-1</sup>	SiO2 mg L <sup>-1</sup>	<sup>18</sup> O/ <sup>16</sup> O (‰ VSMOW)	D/H
Average Rainfall	-	-	-	0.64	1.33	3.09	0.83	0.04	0.01	0	0.02	1.38	12.43	1.09	0.07	-	-
E-Ditch	6.65	290	25.7	4.3	1.9	31.4	16.3	0.04	0.03	0.08	3.66	3.83	156.51	13.56	2.2	-2.07	-9.1
N1-100	5.73	133	24	9.3	1.5	29.6	15.4	0.06	0.03	0.09	2.25	7.81	163.77	8.08	15	-1.8	-9.2
N1-15b	6.68	770	26.5	47.4	1.7	70.7	29.5	13.3	0.2	0.3	2.07	7.74	425.32	37.31	5.2	-1.84	-8.2
N1-40	7.55	358	23.4	12.3	1.5	34.9	15.7	2.23	0.08	0.12	1.77	6.41	192.62	12.56	15.5	-3.41	-18.8
N1-8	6.54	853	25	41.3	1.6	89.2	39.5	7.4	0.2	0.4	2.2	4.38	405.88	140.6	3.2	-2.95	-14.1
N4-15	6.4	221	30.4	0.9	1.3	21.3	7.3	5.28	0.1	0.07	1.31	1.53	73.64	20.27	3.9	-4.52	-26
N4-80	7.21	280	26.7	3.7	1.2	25.1	13.2	0.14	0.02	0.07	1.08	3.94	142.27	1.83	8.2	-3.38	-17.4
N4-FL	8.26	246	26.6	13.7	10.6	21.4	3.4	0.1	0.01	0.25	2.76	9.1	85.99	19.75	10.7	-1.55	-6.1
N-Pond	7.27	540	28.8	3.8	2.3	42.8	22.3	0.05	0.03	0.12	2.66	3.23	230.8	8.97	2.5	1.06	6.8
Outflow	7.39	359	26	3.6	2.1	31.7	16.3	0.13	0.03	0.09	1.57	4.21	156.86	17.72	1.9	-2.13	-10.7
S-10	6.29	1264	27.5	21.3	2.8	105.6	50.6	32.75	0.07	0.01	1.47	25.59	654.93	0.48	6.1	-2.03	-8.6
S-14	5.1	74	28.5	2.5	0.9	6.1	1.5	1.46	0.03	0.01	0.1	6.68	22.23	2.46	2.1	-2.75	-13.2
S-2	6.18	136	32.9	1	0.9	14.3	2.8	1.18	0.03	0.04	0.11	2.1	59.76	0.5	1.8	-3.14	-15.7
S-5	5.43	57	29.2	1.1	1	6.4	2.5	0.04	0.01	0.01	0.23	2.54	25.89	4.01	2.2	-3.95	-20.8
S-7	6.07	222	27.9	7.2	1.3	12	6	9.75	0.03	0.04	0.25	9.36	90.74	1.04	9	-2.18	-10.7
S-8	5.2	130	25.3	3.6	1.1	5.6	3.3	5.1	0.01	0.01	0.11	4.18	14.94	25.97	2.3	-3.29	-15.9
W1-100	7.33	365	22.9	10	1.6	34.4	18.3	0.16	0.02	0.07	1.57	7.49	199.72	6.69	20.2	-2.09	-10.5
W1-40	5.29	110	22.8	6.4	1.2	9.3	4	0.4	0	0.1	0.63	10.79	46.43	0.64	6	-1.81	-8.9
W1-8	6.41	804	26	44.3	1.7	76.2	31.1	16.9	0.2	0.3	1.75	6.59	326.49	159.49	6.3	-2.26	-9.7
W4-15	6.12	588	27.9	6.1	1.8	46.7	27.3	8.82	0.05	0.02	0.84	11.51	293.74	0.13	4.9	-3.6	-17.6
W4-80	7.2	579	25.9	72.2	2.2	35.7	20.7	0.6	0.1	0.1	1.6	7.18	345.54	36.2	6.2	-2.45	-14.5
W4-FL	6.54	306	25.4	10.4	1.3	33.8	7.3	0.08	0.02	0.05	0.85	6.72	152.07	2.33	0.8	1.33	6.8
W-Ditch	6.79	246	31.5	3.4	0.9	23.1	7.9	0.29	0.04	0.09	0.46	5.05	78.12	25.73	1.8	-1.26	-5.8

Appendix IIIa. Dry season results of mass-balance mixing modeling using sodium. End members are CSA water and rainfall/ambient surficial and surface water.

Water Type (dry season)	Na	CSA water Contribution	Rainfall/ Ambient Water
	(mg/L)	Proportion	Proportion
Rainfall/Ambient Water	0.83	0	1
S-10	16.10	0.58	0.42
S-7	9.17	0.34	0.66
N-Pond	7.76	0.29	0.71
E- Ditch	7.05	0.27	0.73
W1-40	6.75	0.26	0.74
W4-15	6.30	0.24	0.76
W-Ditch	5.83	0.23	0.77
S-8	4.62	0.19	0.81
Outflow	4.55	0.18	0.82
N1-40	3.68	0.15	0.85
S-14	3.40	0.14	0.86
S-5	1.04	0.06	0.94
CSA water	36.27	1	0



Appendix IIIb. Wet season results of mass-balance mixing modeling using sodium. End members are CSA water and rainfall/ambient surficial and surface water.

Water Type (wet season)	Na	CSA water Contribution	Rainfall/ Ambient Water
	(mg/L)	Proportion	Proportion
Rainfall/Ambient Water	0.83	0	1
S-10	21.30	0.49	0.51
S-7	7.20	0.18	0.82
N-Pond	3.80	0.10	0.90
E-Ditch	4.30	0.11	0.89
W1-40	6.40	0.16	0.84
W4-15	6.10	0.15	0.85
W-Ditch	3.40	0.09	0.91
S-8	3.60	0.10	0.90
Outflow	3.60	0.10	0.90
N1-40	12.30	0.29	0.71
S-14	2.50	0.07	0.93
S-5	1.10	0.04	0.96
CSA water	36.27	1	0