Lateral Macropore Dominated Flow On A Clay Settling Area In The Phosphate Mining District, Peninsular Florida

by

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# TABLE OF CONTENTS

LIST OF FIGURES 
ABSTRACT 
INTRODUCTION 
SITE DESCRIPTION 
  Location and Setting 
  Climate 
  Hydrogeology 
  Vegetation 
METHODS 
  Physical Hydrological Measurements and Analysis 
  Tracer Application and Sample Collection 
  Laboratory Analysis 
RESULTS 
  Applied Tracer 
  North Pond Stages and Groundwater Hydraulic Heads 
DISCUSSION 
CONCLUSIONS 
REFERENCES 
APPENDICIES 
  Appendix i. List of bromide concentrations for core samples in mg/L
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Plan view of the study site.</td>
</tr>
<tr>
<td>2</td>
<td>Fence diagram through the CSA and surrounding hydrological landscape.</td>
</tr>
<tr>
<td>3</td>
<td>Rainfall in cm/d at the CSA immediately before, during, and after the tracer application</td>
</tr>
<tr>
<td>4a</td>
<td>Postplot of bromide concentrations over simple fan sampling area for day 1.</td>
</tr>
<tr>
<td>4b</td>
<td>Postplot of bromide concentrations over simple fan sampling area for week 1.</td>
</tr>
<tr>
<td>4c</td>
<td>Postplot of bromide concentrations over simple fan sampling area for month 1.</td>
</tr>
<tr>
<td>4d</td>
<td>Postplot of bromide concentrations over simple fan sampling area for month 3.</td>
</tr>
<tr>
<td>5</td>
<td>Bromide concentrations over time in the north pond.</td>
</tr>
<tr>
<td>6</td>
<td>Precipitation in cm/d and T1 hydraulic head levels over time.</td>
</tr>
<tr>
<td>7</td>
<td>Precipitation in cm/d and north pond stage above land surface over time.</td>
</tr>
</tbody>
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Lateral Macropore Dominated Flow on a Clay Settling Areas in the Phosphate Mining District, Peninsular Florida,
Natalie E. Pechenik

ABSTRACT

The objective of this study was to use an applied tracer to study lateral ground water flow paths in the top ~0.5 m of clay settling areas (CSA) in order to gain better understanding of hydrologic connectivity of CSAs to the surrounding hydrologic systems. The study site was located on the non-operational Mosaic Fort Mead Mine property in Fort Meade, Polk County, Florida. This lateral tracer test study is a follow up from a vertical tracer test study performed at the same site location in 2007. The CSA is generally composed of a well developed, clay rich, subangular-blocky surface layer ~0.0-1.0m, which exhibits abundant desiccation cracks plus other macropores underlain by a massive, saturated, clay-rich sublayer from ~1.0-2.5 m. A bromide tracer was applied into an injected trench. All 60L of the applied tracer flowed out of the down gradient face of the trench quickly, over an eleven minute period. The Bromide tracer was rapidly transported laterally and was detected as far as 16 m from the starting point just 24 hours after application, as well as in the inundated north pond adjacent to the study area. Bromide concentration distribution was not uniform over the study area during any time period, with an initial disorganized bromide pulse followed by secondary pulse concentrated on the north side of the sampling area. This spatial-temporal distribution of bromide indicates preferential flow through desiccation cracks or other macropores. Bromide concentrations in the north pond increased over time while pond stage fluctuated due to this shallow lateral macropore dominated flow in and out. Although it is most likely true that flow paths from the CSA to the adjacent
hydrologic landscape during the wet season is dominated by rapid shallow lateral flow through macropores, specific flow paths, macropore length, diameter and distribution and fluxes still remain unquantified. Therefore, how the hydrology of CSAs affects the adjacent hydrologic landscape still remain unquantified.
INTRODUCTION

Geologic deposits composed of clay-rich materials typically have low permeabilities (Fetter, 2001) and are typically treated as homogeneous and isotropic deposits (Dekker and Bouma, 1984). Low permeability, clay-rich deposits can perch or confine aquifers (Fetter, 2001; Rains et al 2006), and therefore are often used to retard or restrict flow in or out of solid waste disposal sites and well annuli (Johnson et al., 1989; Sanders, 1998). However, the assumption that clay-rich deposits are homogeneous and isotropic is not necessarily correct in clay-rich deposits with desiccation cracks and other macropores (Thomas and Phillips, 1979; Bouma et al., 1981; Dekker and Ritsema, 1996).

Clay rich deposits have the capability to swell when wetted and shrink when dried due to interlayer water adsorption within the clay (Tuller and Or, 2003). When subjected to repeat near surface wetting and drying events, clay-rich deposits can form well-defined desiccation cracks. The physical attributes of the void spaces are variable due to differences in mineralogy, degree of compaction, grazing or nature of wet and dry cycles (Reid and Parkinson, 1984; Vogel et al., 2005).

Desiccation cracks caused by wet/dry cycles or other bioturbation macropores such as root channels or burrows within a clay-rich deposit can generate preferential flow paths (Thomas and Phillips, 1979; Bouma et al., 1981; Dekker and Ritsema, 1996). Although desiccation cracks and other macropores comprise a small proportion of the total porosity of a clay-rich deposit, they nevertheless can cause substantial enhancements to flow paths, enabling water to bypass the low-permeability matrix and allow for rapid flow across the landscape (Bouma and Dekker, 1978). Therefore desiccation cracks and other macropores can easily dominate and be responsible for
much of the flow and transport through the shallow subsurface of a clay rich deposit (Heppell et al., 2000).

Clay settling areas (CSAs) are clay-rich deposits which are a byproduct of phosphate mining in peninsular Florida. The mineral resource typically lies beneath ~4-8 m of overburden and is ~3-4 m in thickness, and typically is composed of one third various-sized phosphatic sediment, one third sand-sized sediment, and one third clay-sized sediment (Florida Institute of Phosphate Research, unpublished data). One byproduct of the phosphate beneficiation processes is a clay-rich slurry, which is composed of ~3% solids, typically has a d<sub>50</sub> of <0.2 microns (Hawkins, 1973). This clay slurry is pumped to CSAs, which are reservoirs contained by earthen berms, ~6-15 m above grade and ~120-320 hectares in size (Lewelling and Wylie, 1993; Zhang and Albarelli, 1995). Once pumped into the CSA, the clay slurry quickly consolidates and excess water is drained off resulting in ~18-22% solids within a few months and a surface crust that is ~50-60% solids after 5 years, although the deeper subsurface will remain ~25% solids for an unknown amount of time (Zhang and Albarelli, 1995; Erwin et al., 1997).

Phosphate mining operations are still active in peninsular Florida. As of 1998, there were ~120,000 hectares of mined land, ~50,000 hectares of which was covered with CSAs (Stricker, 2000). Over the life span of all phosphate mining operations, the total mined land could be ~175,000 hectares of mined land, ~70,000 hectares of which could be covered with CSAs. There are no typical CSAs, in that CSAs vary in size, thickness, height above grade, proximity to other CSAs, and/or age (Murphy et al., 2008).

Despite their abundance, little research has been done on the hydrology of CSAs and their effects on surrounding hydrologic systems and water resources. CSAs were long conceptualized as being precipitation sinks, with large evapotranspiration outflows, minimal surface water outflows, and negligible groundwater outflows. This capture-zone concept implies that the effective size of a drainage basin is reduced due to the presence of a CSA, yet little
research has been done to quantify this theory. Even basic hydrologic processes of CSAs are still poorly understood (Lewelling and Wylie, 1993; Zhang and Albarelli, 1995; Murphy et al. 2008).

This study is part of a larger four-year study of CSAs and supplemental to a previous hydrologic investigation of one particular CSA. The preceding study performed by Murphey et al. (2008) indicated that the simple assumption that CSAs are precipitation sinks, with large evapotranspiration outflows, minimal surface water outflows, and negligible groundwater outflows may be incorrect. Instead, Murphy et al. (2008) suggested that CSAs possess perched surface-water and groundwater flow systems and deep groundwater flow systems, with both flow systems discharging into the surrounding hydrologic landscape. However, unanswered questions remained, including specific details of the mechanisms and flow paths by which water flows through the perched surface-water and groundwater flow systems. The objective of this study was to answer some of those questions, by using an applied tracer and shallow monitoring wells to better understand the mechanisms and flow paths by which water flows through the perched surface-water and groundwater flow systems.
SITE DESCRIPTION

LOCATION AND SETTING

The study site is located near Fort Meade, Polk County, Florida (Figure 1). The CSA is ~20 years old and is ~6 m above grade and ~75 hectares in size. The surface crust of the CSA is well developed and can support vehicles during both the wet and dry seasons. Though the surrounding area was mined, the CSA in question is located on un-mined land so the bottom boundary conditions are reasonably well understood. The surface of the CSA slopes slightly from north to south, with the surface varying from nearly level to undulating (Figure 2). The southwest face of the earthen berm slumps slightly, generating a slight slope towards the southwest corner of the CSA and the adjacent field.

CLIMATE

The climate at the study site is sub-tropical with relatively hot, humid summers and warm dry winters. Summer rainfall is frequent and can be of high intensity and is typically due to localized convective thunderstorms, while winter rainfall is less frequent and is typically due to continental cold fronts (Lewelling and Wylie, 1993). Mean (± standard deviation) annual precipitation is 135.3 (± 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 in the area was 103 cm for water year 2008, so rainfall was lower than
normal in during the course of this study (Southeastern Regional Climate Center data for Bartow, Florida for water year 2008).
Figure 1. Plan view of the study site.
Figure 2. Fence diagram through the CSA and surrounding hydrological landscape. Points in the inset and on the cross section are in the same locations. Vertical exaggeration is ~20x.
HYDROGEOLOGY

There are three principal hydrostratigraphic units that compose the central Florida phosphate mining district: the surficial aquifer, the intermediate aquifer system and the deep Floridan aquifer system (Erwin et al., 1997). The phosphate-rich sediment is mined from the upper part of the intermediate aquifer in the Bone Valley Member, which is located within the Miocene-aged Hawthorn Formation.

The berms of the CSA are composed of sand-rich overburden from the local surficial aquifer. The clay slurry deposited into the CSA is composed of clay from the Bone Valley Member mixed with local groundwater and other processing waters (Reigner and Winkler, 2001). Currently, the CSA is generally composed of a well developed, clay-rich, subangular-blocky surface layer ~0-0.5 m, which exhibits abundant desiccation cracks plus other macropores underlain by a massive, saturated, clay-rich sublayer from ~0.5-2.5 m (Murphy et al. 2008). This observation is based upon 38 boreholes, two shovel test pits, and two front-loader test pits at various locations on the CSA. Based upon observations at six deep boreholes, the massive, saturated, clay-rich sublayer is ~5-6 m in thickness and underlain by un-mined sands of the surficial aquifer.

Although there are no surface water inflows, there are surface water outflows via engineered culverts through the east berm. There may also be groundwater outflows through the berms (Murphy et al. 2008). The CSA surface has at least seven closed-basin depressions of various size and shape that seasonally pond with water. The closed-basin depressions on the CSA have no surface water inflows or outflows, so surface-water levels are controlled by precipitation, evapotranspiration, and groundwater throughflow (Murphy et al, 2008).
VEGETATION

Invasive Cogan Grass, (*Imperata cylindrica* (L.) Raeuschel) composes upwards of ~65% of the vegetation on the CSA. The remaining ~35% of the CSAs surface is composed of mixed hardwoods. The uplands exhibit the invasive Earleaf Acacia (*Acacia auriculiformis* A. Cunn. Ex. Benth) while the seasonally inundated closed depressions consist of native Coastal Plain Willows (*Salix floridana* Chapm.).
METHODS

Both physical and chemical hydrological methods were used for this study. All data were collected during the 2008 calendar year.

PHYSICAL HYDROLOGIC MEASUREMENTS AND ANALYSIS

Precipitation was measured continuously with an ET106 Weather Station (Campbell Scientific, Inc., Logan, Utah). On-site weather station data were not available from January 1-March 12 at 10:00 AM due damage from a wildfire that occurred the previous year. Therefore, precipitation data were only available beginning March 12 at 10:00 AM.

Hydraulic head in the shallow subsurface of the upland (hereafter referred to as T1) and in a down-gradient closed-basin depression (hereafter referred to as the north pond or W1) were measured at 10-minute intervals with pressure transducers and dataloggers (Solinst Canada, Ltd., Georgetown, Ontario, Canada). T1 and W1 both had 5 cm inside diameter PVC standpipes. T1 was installed in a 100 cm wide, 30 cm long, and 50 cm deep trench backfilled with sand and capped with a cement surface seal to ensure that measured hydraulic heads were representative of mean macropore hydraulic heads. T1 was screened from 25-50 cm below the ground surface. The blank tip of the screen was below 50 cm, so any measured water levels >50 cm below the ground surface was due to residual water. W1 was installed in a 30 cm diameter borehole backfilled with sand but not capped with a cement surface seal.
Bromide was used as an applied tracer to study shallow vertical and lateral groundwater flow paths. Bromide was chosen because background concentrations were naturally low (McCutcheon et al., 1993; Murphy et al. 2008).

A 100 cm wide, 25 cm long, and 50 cm deep trench was dug perpendicular to the apparent flow path on the northern part of the CSA. All faces of the trench, excluding the down-gradient face, were lined with plastic to direct all flow down gradient. On July 21 at ~1:00 PM, 60 L of 50 g/L LiBr solution was introduced into the trench. All 60L of the solution infiltrated in ~11 minutes. The trench was then backfilled with parent material.

Porewaters were collected from core samples taken with an open-barrel hand auger at 0, 2, 4, 8, and 16 m away in a 45° fan shape from the trench. Cores were augured no deeper than 0.5 m and were placed into wide-mouthed 300 mL HDPE sample bottles. One sample was collected at 0 m, three samples were collected at 1 m, five samples were collected at 2 m, seven samples were collected at 4 m, nine samples were collected at 8 m, and 11 samples were collected at 16 m. An additional surface-water sample was collected from the north pond just beyond the 16 m sample area. Samples were collected five times in total: the initial day of the injection (July 21), one day after the injection (July 22), one week after the injection (July 29), one month after the injection (August 22), and three months after the injection (October 27). After each hole was augured, it was backfilled with native material to minimize down-borehole contamination.

A hydraulic sediment squeezer was used to extract porewaters from the core samples (Manheim et al., 1994). Core samples were subjected to 200-250 psi. Extracted porewaters were filtered through two 0.45 μm in-line filters and collected in 10 mL syringes. After at least 1.5 mL of porewater was collected in the syringe, porewater samples were transferred to 30 mL HDPE sample bottles. Each sample took approximately 30-60 minutes to extract, and was composed of a
minimum of 1.5 ml and a mean of 1.8 mL of water. Surface water from the north pond was filtered through one 0.45 μm in-line filters and placed directly into 30 mL HDPE sample bottles.

LABROTORY ANALYSIS

Bromide analyses were conducted at the University of South Florida Center for Water Analysis. Bromide concentrations were determined by ion chromatography following the EPA 300 method (Clesceri et al., 1998). All samples were kept at the method-required 4º C prior to analysis. Analytical precision of the laboratory analyses were better than 1%.
RESULTS

APPLIED TRACER

No rainfall occurred between the injection and the day one sample collection, but rainfall began soon thereafter and persisted episodically throughout the duration of tracer test (Figure 3). Despite the lack of rainfall between the injection and the day one sample collection, the bromide was nevertheless transported rapidly across the CSA immediately following the injection (Figure 4). At day one, the bromide was detected 16 m from the injection, with concentrations largely focused toward the left side of the sample fan. At week one and month one, bromide was still detected at 16 m from the injection, with concentrations more focused toward the right side of the sample fan. At month three, bromide continued to be detected, though concentrations were lower but still spread non-uniformly throughout the sample fan. Meanwhile, bromide concentrations increased steadily over time in the north pond, just down gradient of the 16 m sample area (Figure 5).

At no point during the three month sampling period was distribution of bromide concentration over the entire sample area uniform. Mean (± standard deviation) bromide concentrations over the entire sample area were 1.42 (± 1.59) mg/L on day one, 10.01 (± 44.81) mg/L on week one, 3.02 (± 4.36) mg/L on month one, and 2.93 (± 6.46) mg/L on month three. Minimum and maximum bromide concentrations over the entire sample area were found on day one and week one, respectively.
From June 1-June 25, there was 17 cm of total rainfall. However, all of this rainfall was either lost to evapotranspiration or went into shallow groundwater storage as there was no groundwater in T1 or W1 in response to any of these rainfall events. From June 26-28, 5.59 cm of rainfall occurred, with groundwater levels in W1 and T1 finally rising (Figures 6 and 7). Thereafter, both T1 and W1 responded rapidly to rainfall, with rapid hydraulic head rises and falls, indicating rapid infiltration and lateral flow through the shallow subsurface. From June 1-October 27, minimum and maximum stages at T1 were 49.1 cm below lands surface (October 10) and 3.64 cm above lands surface (August 19), respectively and at W1 were 21.03 cm (July 7) and 78.63 cm (August 31) above the ground surface, respectively. Rapid macropore flow was evident in T1, where hydraulic heads less than or equal to 50 cm below lands surface rose and fell rapidly in response to rainfall. After two consecutive precipitation events on June 26 and 27, a total of 5.58 cm of precipitation fell and the hydraulic head increased by 41.75 cm to 8.25 cm below lands surface by June 28. The next day, June 29, no precipitation was recorded, and the hydraulic head dropped by 15.21 cm to 23.49 cm below lands surface. The day after that, June 30, a subsequent drop of 9.75 cm was recorded with a total head of 33.24 cm below lands surface. In total the pressure transducer at T1 recorded a head drop of ~24.99 cm below lands surface over a 48 hour precipitation free period during which storage was already satisfied. This magnitude of head drop is greater than would be expected from ET, which according to Murphy et al (2008) is ~0.5 (±0.1) cm/d.
Figure 3. Rainfall in cm/d at the CSA immediately before, during, and after the tracer application. Arrows indicate core sampling dates on Day 0, Day 1, Week 1, Month 1, and Month 3, respectively.
Figure 4a. Postplot of bromide concentrations over simple fan sampling area for day 1. The size of the circles is proportional to bromide concentration.
Figure 4b. Postplot of bromide concentrations over simple fan sampling area for week 1. The size of the circles is proportional to bromide concentration.
Figure 4c. Postplot of bromide concentrations over simple fan sampling area for month 1. The size of the circles is proportional to bromide concentration.
Figure 4d. Postplot of bromide concentrations over simple fan sampling area for month 3. The size of the circles is proportional to bromide concentration.
Figure 5. Bromide concentrations over time in the North Pond.
Figure 6. Precipitation in cm/d and T1 hydraulic head levels over time.
Figure 7. Precipitation in cm/d and north pond stage above land surface over time.
DISCUSSION

The Murphy et al. (2008) had previously suggested that shallow subsurface groundwater flow and transport and the seasonal inundation of closed-basin depressions on the CSA were controlled by rapid lateral flow through desiccation cracks and other macropores. This assumption was based upon a vertical tracer test performed at the same CSA. During the vertical tracer test, bromide concentrations decreased over time without penetrating to depths greater than ~0.5 m at any time and with only a minor amount of bromide uptake attributed to plant uptake (Whitemer et al., 2000; Murphy et al., 2008).

During the initial phases of the lateral tracer test, it was evident that some flow path other than flow through the clay matrix alone was responsible for flow through the upper ~0.5 m of the CSA. All 60L of the 60g/L LiBr solution infiltrated in ~11 minutes and was detected up to 16 m away just one day later. This could not have occurred through the clay matrix alone, which has an estimated hydraulic conductivity of $10^{-5}$-$10^{-7}$ m/d (Morris and Johnson, 1967; Davis, 1969). Flow through preferential flow paths, such as desiccation cracks and other macropores, must have occurred.

The sample fan slight sloped from northeast to southwest, and although bromide concentrations indicated flow and transport over the entire sample fan, concentrations were not uniform or typical of flow and transport though a homogeneous and isotropic medium. One day after the injection, there was a disorganized initial pulse, with bromide transport in multiple down-gradient directions, but with more bromide focused toward the left side of the sample fan. One day and one month after the injection, there was a second pulse, with more bromide focused toward the right side of the sample fan. Three months after the injection, concentrations were
lower and still non-uniformly distributed throughout the sample fan. These inconsistencies may have been due to changes in soil moisture content, resulting in swelling or clays and changing in the distribution and dimensions of desiccation cracks and other macropores.

This rapid macropore flow moves groundwater rapidly into the closed-basin depressions on the CSA. Although low, bromide concentrations were nevertheless detected in the north pond just one day after the injection, and continued to increase throughout the course of the three-month test. This confirms the hypothesis of Murphy et al. (2008), who had suggested that flow through macropores controlled stages in the north pond based upon the results of a water balance which showed that pond stages rose and fell more rapidly than could be due to precipitation and evapotranspiration alone.

These results indicate that preferential flow through desiccation cracks and other macropores dominates flow and transport in the perched groundwater flow system in the upper ~0.5m of the CSA. In the early wet season, rainfall infiltrates and is either lost to evapotranspiration or is taken into soil moisture storage. Once soil moisture storage is filled, subsequent rainfall infiltrates rapidly, perches on top of the massive clay unit at ~0.5 m in depth, and flows laterally through desiccation cracks and other macropores. These flows can then intersect and flow through the closed-basin depressions, which are depressional features inset into the shallow, perched groundwater flow system.
CONCLUSIONS

The results of this study indicate that older CSAs can support shallow, perched groundwater flow systems in which shallow groundwater flow is dominated by flow through desiccation cracks and other macropores. Interconnected desiccation cracks and other macropores that form over time in the top ~0.5 m of the CSA due to shrinking, swelling and subsequent cracking of the clays, root channels, and/or bioturbation are the specific fast flow paths responsible for the observed efficient flow and transport. As suggested by Murphy et al. (2008), these rapid flows largely control stages in the seasonally-inundated, closed-basin depressions on the CSAs. Exact desiccation crack and other macropore length, diameter, and distribution, and the effect of the desiccation cracks and other macropores on the effective hydraulic conductivity of the upper 0.5 m of the CSA, remain unquantified.
REFERENCES


LIST OF APPENDICIES
Appendix i. List of bromide concentrations for core samples in mg/L.

<table>
<thead>
<tr>
<th>sample</th>
<th>7/22/2008 (Day 1)</th>
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