Hydrogeophysical quantification of infiltration and recharge through soil-filled sinkholes using Time Domain Reflectometry and Electrical Resistivity Tomography

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ABSTRACT

This dissertation presents the results of a detailed physical and hydrogeophysical study of two soil-filled sinkholes mantled by ancient New River fluvial terrace deposits. Research was performed at the Virginia Tech Kentland Experimental Farms in Whitethorne, Virginia, USA between fall 2003 and spring 2007, and focused on characterizing infiltration, deep drainage, and recharge through soil-filled sinkholes. Using hydrogeophysical methods, the spatial and temporal distribution of soil moisture was modeled and potential recharge was quantified in two soil-filled sinkholes.

Access-tube time domain reflectometry (TDR) was used to derive one-dimensional (1-D) soil moisture profiles. During access-tube installation, 470 soil samples were obtained from depths between 0.3 and to 9.0 m and characterized both physically and chemically. Using these data, a TDR calibration method was developed. Physio-chemical, TDR moisture, and 1-D electrical resistivity tomography (ERT) data were used to derive a numerically optimized form of Archie's Law which was used to convert ERT measurements into volumetric soil moisture. These results led to development of 2-D ERT-derived distributions of soil moisture in three transects across the two sinkholes in two terraces. Potential recharge was quantified using time-series ERT data with comparison to modeled cumulative potential evapotranspiration (PET) and cumulative precipitation between May 17 and October 9, 2006. The patterns of ERT-derived potential recharge values compared well with those expected from PET and precipitation data. Over the monitoring period from late spring to early fall during this study, results showed that a period of intense rain followed by a 31-day period of consistent rain, in which the rate of precipitation was equal to or exceeded PET, were the only periods in which significant amounts of potential recharge occurred (from 19 to 31% of cumulative precipitation during the study). Spatial distributions of ERT-derived moisture clearly revealed that significant amounts of infiltration occurred on sinkhole flanks and bottoms. Runoff during periods of intense rain flowed to the topographically lowest point in the sinkholes where it infiltrated and resulted in localized zones of enhanced infiltration and potential recharge to the water table.

DEDICATION

This dissertation would not have been completed without the understanding and unwavering support of my wonderful wife, Corinne Schwartz.

Cori, I dedicate this dissertation to you.
Thank you for all your sacrifices.

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ATTRIBUTIONS

Chapter two was submitted as a manuscript to *Soil Science Society of America Journal* "Schwartz, B.F., Schreiber, M.E., Pooler, P.S., and Rimstidt, J.D., *Methods for obtaining accurate access-tube TDR moisture in deep heterogeneous soils*. B.F. Schwartz was responsible for conceiving the project, collecting, interpreting, and analyzing all samples and data, preparing figures and writing the manuscript. M.E. Schreiber helped by clarifying text and reviewing the manuscript. P.S. Pooler assisted with multiple linear regression statistical analysis and performed categorical linear regression modeling. P.S. Pooler also contributed to a figure illustrating the categorical linear regression results. J.D. Rimstidt assisted with statistical and error analyses and manuscript review.

Chapter three was written as a manuscript in preparation for submission to a peer-reviewed journal. B.F. Schwartz was responsible for conceiving the project, collecting, interpreting, and analyzing all data, preparing all figures and writing the manuscript. M.E. Schreiber helped clarify the text and reviewed the manuscript. T. Yan performed numerical optimization of Archie's Law using U-Code and provided documentation for and assistance in interpretation of the model results. W. L. Daniels helped clarify a figure describing soil horizons at the Kentland Experimental Farms.

Chapter four was written as a manuscript in preparation for submission to a peer-reviewed journal. B.F. Schwartz was responsible for conceiving the project, collecting, interpreting, and analyzing all data, preparing all figures and writing the manuscript. M.E. Schreiber helped clarify the text and figures and reviewed the manuscript.

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US Department of Education GAANN Fellowship
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CHAPTER 1

INTRODUCTION

Sinkholes are often the most visible features in karst terrains and are an integral component of most karst systems in the eastern United States. Sinkholes formed by dissolution are generally considered to be part of the epikarst, which is a complex, diverse, and very heterogeneous zone lying between the land surface and underlying un-weathered carbonate bedrock (Klimchouk, 2004). Factors such as bedrock lithology and structures, climate, and soil cover all play important roles in the development of different epikarst properties and morphologies. For similar reasons, sinkholes themselves are complex, diverse and heterogeneous, both with respect to their physical properties and their geographic distribution. Within the classification of sinkholes created by dissolution (as opposed to collapse sinkholes), there is one type which is of special interest to many: the soil-filled sinkhole. In many agricultural regions, soil-filled sinkholes are often subtle features which are utilized for agriculture in a similar manner as the surrounding areas. There are many unresolved questions concerning the ability of these sinkholes to transport water and dissolved contaminants into underlying aquifers, whether better management practices (BMPs) should be implemented within the sinkholes, and, if so, how to best define the area in which to apply these BMPs. At the root of all these questions is the basic issue of whether soil-filled sinkholes transmit water and contaminants to the underlying aquifer more or less efficiently than surrounding areas. Common sense indicates that they should be more efficient in transmission of water and contaminants; though there is little empirical evidence to support this conclusion.

The research presented in this dissertation focuses on characterizing and quantifying the spatial and temporal distribution of infiltration and recharge in sinkholes with thick soil mantles. In particular, I studied volumetric soil moisture changes in two sinkholes in two sinkhole plains which developed in ancient New River terrace deposits on the Virginia Tech Kentland Experimental Farms in Montgomery County, southwest Virginia, USA. The weathered deposits in these terraces are the source of most of the thick soils overlying carbonate bedrock at the study site. Soil mantles range in thickness from 3 m to greater than 12 m and, due to their parent materials, are highly heterogeneous with regard to texture and physio-chemical properties.

As with many proposed research projects, answering specific research questions was not as straightforward a task as was initially envisaged. The problem of measuring soil moisture at the field site seemed fairly straightforward until fieldwork began. Some of the difficulties encountered were related to limitations with instrument installation methods, instrument calibration difficulties, heterogeneities in soils, and an unexpectedly deep soil profile. These difficulties led to the development of new methods for installing instrumentation and calibrating measurements, for measuring the spatial distribution of soil moisture in very thick and heterogeneous soil profiles, and for quantifying infiltration and potential recharge at the field-scale. This dissertation is organized into three main chapters, prepared as three separate manuscripts, which are currently either in review or in preparation for submission to scientific journals. The papers are described below.

METHODS FOR OBTAINING ACCURATE ACCESS-TUBE TDR MOISTURE IN DEEP HETEROGENEOUS SOILS

Time domain reflectometry (TDR) is an accepted method for measuring soil moisture, and access-tube TDR is commonly used to measure 1-D soil moisture profiles up to 3 m in depth. However, the technique has several limitations which are related to TDR's insensitivity to certain fractions of soil moisture (Jacobsen and Schjonning, 1993), and methods which were unsuitable for installing access-tubes to depths of up to 9 m (Whalley et al., 2004). Chapter 2 of this dissertation presents methods I developed to install TDR access-tubes in deep soils and to later calibrate access-tube derived TDR measurements. To obtain correct soil moisture values using TDR, I developed a physico-chemical method for calibrating access-tube TDR soil moisture measurements using measured soil properties from 470 soil samples. I present two important findings: 1) that access-tube TDR soil moisture measurements are not representative of true soil moisture content in most soil textures and cannot be used to accurately calculate volumetric soil moisture without calibration, and 2) that TDR moisture measurements can be calibrated to true moisture content by multiple linear or categorical linear regression modeling of several important physical and chemical parameters. The calibration dominantly corrects for water which is partially undetectable by TDR due to various physical and chemical mechanisms of water immobilization. The model was used to calibrate time-series measurements by first applying the calibration equation which correct for the physico-chemical effects. A final calibration of time-series measurements was then obtained by adding the change in uncalibrated TDR moisture at the time of interest relative to the TDR moisture reading at the time of initial measurement and calibration. This method makes two important assumptions: 1) that the TDR probe is accurately measuring 'free' moisture content and any subsequent changes in moisture content, and 2) that the TDR-undetectable moisture content remains essentially constant.

LINKING FIELD SCALE ELECTRICAL RESISTIVITY TOMOGRAPHY AND TIME DOMAIN REFLECTOMETRY DERIVED SOIL MOISTURE

1-D quantification of soil moisture distribution using TDR showed that significant field-scale heterogeneities existed in both sinkholes, which prevented simple 2-D modeling of soil moisture. Because ERT measurements in unsaturated soils are sensitive to soil moisture (Shuyun and Yeh, 2004; Sreedeep and Singh, 2005), I used 2-D ERT data as the foundation for obtaining 2-D soil moisture measurements. Chapter 3 presents research which resulted in a method for quantitatively measuring soil moisture in 2-D field-scale profiles. Using data derived in part from the TDR calibration work, I converted the 2-D ERT data into 2-D models of volumetric soil moisture using a modified and numerically optimized form of Archie's law (Shah and Singh, 2005) which includes ERT-derived bulk conductivity measurements, percent clay, and pore water conductivity estimates using one of two methods: soluble salts or an extractable cation proxy. The extractable cation model produced slightly better results. The results suggested that both proxy methods are suitable substitutes for actually measuring pore-water conductivity: a time consuming and expensive task. When calibrated to TDR-derived soil moisture measurements, my final results showed that field-scale 2-D ERT profiles can successfully be converted into 2-D soil moisture models with one standard deviation in soil moisture of $\pm$ 6%. The ability to convert field scale ERT measurements into profiles of soil moisture is a valuable tool for quantitatively assessing soil moisture distribution in soils and the methods discussed in this chapter are also applicable to time-series and 3-D moisture modeling at a variety of scales.

QUANTIFYING POTENTIAL RECHARGE THROUGH THICK SOILS IN MANTLED SINKHOLES USING ERT DATA

Quantifying infiltration through soil-filled agricultural sinkholes is an important step towards characterizing how this type of karst feature contributes to recharge entering karst aquifers.

Understanding the spatial and temporal distribution of infiltration and recharge is critical information for modeling water quantity and quality (Bohlke, 2002; de Vries and Simmers, 2002). This is especially important at the intermediate or field scale, as this is the scale at which many water quality problems exist. Chapter 4 presents methods for quantifying field-scale infiltration and potential recharge using time-series ERT data. Expanding on the methods and results presented in chapters 2 and 3, I used time-series ERT data from May 17 to October 9, 2006, cumulative precipitation records, and cumulative modeled potential evapotranspiration (PET) to quantify rates and amounts of infiltration and potential recharge through the two soil-filled sinkholes. Although the results of this study are specific to the study site, several important conclusions were reached. First, infiltration and potential recharge occurs via several mechanisms in soil-filled sinkholes and can be divided into two components: 1) rapid infiltration via macropores, and 2) diffuse infiltration through the porous unsaturated soils. The methods presented here were used to measure diffuse infiltration, although high temporal resolution of ERT can produce better resolution of rapidly infiltrating water. Second, soil-filled sinkholes at this study site clearly contribute significant amounts of recharge via both rapid and diffuse mechanisms. During normal conditions, this type of sinkhole should probably be modeled as an environment closer to that which exists on topographic highlands around sinkholes: a region of potentially rapid infiltration and recharge via macropores, but with a significant diffuse recharge component as well. Intense rains causing overland flow enhance the volume of infiltration at the lowest points in the sinkholes. This indicates that under these conditions soil-filled sinkholes should still be treated as regions with greater potential for contamination than the surrounding uplands.

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