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Contaminant Transport Through Aquitards:

Technical Guidance for Aquitard Assessment

Subject Area:
Environmental Leadership

Contaminant Transport Through Aquitards: Technical Guidance for Aquitard Assessment

Awwa Research Foundation

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The Foundation's mission is to advance the science of water to improve the quality of life. To achieve this mission, the Foundation sponsors studies on all aspects of drinking water, including supply and resources, treatment, monitoring and analysis, distribution, management, and health effects. Funding for research is provided primarily by subscription payments from approximately 1,000 utilities, consulting firms, and manufacturers in North America and abroad. Additional funding comes from collaborative partnerships with other national and international organizations, allowing for resources to be leveraged, expertise to be shared, and broad-based knowledge to be developed and disseminated. Government funding serves as a third source of research dollars.

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Contaminant Transport Through Aquitards: Technical Guidance for Aquitard Assessment

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CONTENTS

TABLES

FIGURES

FOREWORD

The Awwa Research Foundation is a nonprofit corporation that is dedicated to the implementation of a research effort to help utilities respond to regulatory requirements and traditional high-priority concerns of the industry. The research agenda is developed through a process of consultation with subscribers and drinking water professionals. Under the umbrella of Strategic Research Plan, the Research Advisory Council prioritizes the suggested projects based upon current and future needs, applicability, and past work; the recommendations are forwarded to the Board of Trustees for final selection. The foundation also sponsors research projects through the unsolicited proposal process; the Collaborative Research, Research Applications, and Tailored Collaboration programs; and various joint research efforts with organizations such as the U.S. Environmental Protection Agency, the U.S. Bureau of Reclamation, and the Association of California Water Agencies.

This publication is a result of one of these sponsored studies, and it is hoped that its findings will be applied in communities throughout the world. The following report serves not only as a means of communicating the results of the water industry's centralized research program but also as a tool to enlist the further support of the nonmember utilities and individuals.

Projects are managed closely from their inception to the final report by the foundation's staff and large cadre of volunteers who willingly contribute their time and expertise. The foundation serves a planning and management function and awards contracts to other institutions such as water utilities, universities, and engineering films. The funding for this research effort comes primarily from the Subscription Program, through which water utilities subscribe to the research program and make an annual payment proportionate to the volume of water they deliver and consultants and manufacturers subscribe based on their annual billings. The program offers a cost-effective and fair method for funding research in the public interest.

A broad spectrum of water supply issues is addressed by the foundation's research agenda: resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide the highest possible quality of water economically and reliably. The true benefits are realized when the results are implemented at the utility level. The foundation's trustees are pleased to offer this publication as a contribution toward that end.

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EXECUTIVE SUMMARY

Aquitards are low-hydraulic conductivity geologic deposits that can be relatively extensive and thick. Aquitards restrict the flow of groundwater to adjacent, high-conductivity formations that form *aquifers,* and aquitards can help protect adjacent aquifers from contamination. The presence or absence of an aquitard and the degree to which it confines, or restricts flow to, an adjacent aquifer is critical to evaluating the susceptibility of the aquifer to various contaminants.

This guidance document is intended for use by municipal water system managers, their technical consultants, and others who need to understand how to evaluate aquitards. A companion document prepared by the same research group (*Contaminant Transport Through Aquitards: A State-of-the-Science Review*) summarizes the current knowledge of aquitard science.

REPORT OBJECTIVES

The Awwa Research Foundation (AwwaRF) funded this study to determine the best methods for water utilities and their technical consultants to evaluate how aquitards protect water supply wells and aquifers from contamination, and how to evaluate aquifer susceptibility in the presence of aquitards. The objective of this document is to summarize specific technical methodologies and categories of data collection and synthesis. Accordingly, this report is arranged as a technical manual, and literature references are provided only where they illustrate particular techniques. *Contaminant Transport Through Aquitards: A State-of-the-Science Review* provides a detailed guide to the literature.

APPROACH

The project team that developed this manual is a diverse group of hydrogeologists with cumulative experience in aquitard hydrogeology across a variety of geological settings. In developing this manual the authors have relied on personal experience, published literature, contacts with professional colleagues, and findings from specific field investigations carried out for this project at several field sites in Wisconsin. Based on the companion *State-of-the-Science* report, the authors selected methods and techniques that show the most promise for effective aquitard evaluation at reasonable expense.

In order to facilitate readability and use, this document divides the evaluation methodologies into a series of categories. Chapter 1 discusses an overall strategy for studying aquitards in the context of susceptibility to contamination and outlines the important role of *conceptual models* in executing this strategy. Chapter 2 provides background information about transport pathways through aquitards and critical characteristics of common contaminants. Chapters 3 through 9 summarize a series of proven methodologies and techniques for geologic characterization (chapter 3), drilling (chapter 4), characterizing boreholes and core (chapter 5), testing and sampling of an aquitard from an open borehole (chapter 6), constructing monitoring systems (chapter 7), estimating hydraulic conductivity of aquitards (chapter 8), and assessment of transport through aquitards (chapter 9). These chapters illustrate each technique with references from the literature and, where appropriate, with specific examples from field sites that we have worked at. Chapter 10 discusses compiling various data sets collected from an aquitard to draw conclusions about protecting drinking water supplies at various spatial scales. Many of the examples provided in the report come from an aquitard study conducted near Madison, Wis. (described in Appendix A). This study was conducted by the project team during 2003 and 2004 to ground-truth many of the methods described in the report.

RECOMMENDATIONS

An appropriate protocol for aquitard studies moves from relatively simple and inexpensive mapping activities to sophisticated data collection and analyses. We recommend that most aquitard studies follow a similar stepwise procedure to save time and money. Depending on the issue(s) motivating interest in a particular aquitard, the investigation may differentiate between three primary aspects of aquitard characterization: geologic setting, groundwater flow, and contaminant migration. For example, one might intend to optimize well design (i.e. casing depth, well depth) to increase both contaminant protection and well yield. In other cases, discovery of contamination at a particular well may motivate detailed study of an aquitard. Some projects may be complete after steps 1, 2, and 3 (below), while others will require the extensive data gathering and analyses of steps 4 through 11. Appropriate steps are:

1. Compile existing data (previous studies, maps, well logs, geologic information, etc). Develop a conceptual model of the aquitard geology. Define the lithologic and stratigraphic units composing the aquitard. Construct preliminary maps of aquitard extent and thickness, and determine whether aquitards are present in the area of interest.

2. Combine the geologic conceptual model of the aquitard with available hydraulic data (water table and potentiometric maps) to develop a conceptual model of the groundwater flow system. Determine the regional and local importance of the aquitard and its probable role in the groundwater flow system. Aquitards are generally of interest with respect to adjacent aquifers. This data review and conceptual model should include all significant hydrogeologic units within the flow system.

3. Develop a conceptual model of contaminant transport of constituents of concern. Make preliminary estimates of groundwater velocity and travel times across the aquitard using simple analytical equations. Refine travel time estimates for particular contaminants based on appropriate retardation and/or diffusion parameters.

4. Where existing wells are available, sample for isotopes and other diagnostic chemical constituents to evaluate transport across aquitard of interest.

5. Plan site investigations of the aquitard: assess the importance of determining the presence or absence of preferential contaminant transport pathways (e.g. fractures) through the aquitard. Select methods appropriate to the hydrogeologic setting.

6. Conduct appropriate site investigations: install boreholes, obtain rock core, conduct geophysical investigations, and install multilevel monitoring equipment *within* the aquitard.

7. Prepare detailed data analysis based on new field data, including stratigraphic correlations, aquitard thickness analyses, estimates of aquitard hydraulic properties. Update and refine the flow system conceptual model with new information.

8. Collect and analyze water and core samples for hydrochemical, isotopic, and biologic constituents of interest. Update and refine the contaminant fate and transport conceptual model with new information.

9. Construct and calibrate numerical groundwater flow models at appropriate scales to address the problems at hand. The model(s) may include aquifers as well as the aquitard of interest, to yield insight into flow across a region. Models constructed to evaluate a particular well or contamination site may be more limited in scope.

10. Construct contaminant transport models that include transport and attenuation processes (e.g. retardation, dilution, decay) appropriate to contaminants of concern and to the hydrogeologic conceptual model (e.g. porous medium or fracture flow).

11. Use the models to simulate future conditions, processes, or impacts (e.g. various pumping scenarios, drought, contaminant source areas); draw conclusions.

We recommend the stepwise use of analytical and numerical groundwater flow and solute transport models as tools for data evaluation in most aquitard studies. These models provide a means to integrate aquitard information within the context of groundwater flow systems and spatial heterogeneity, and provide a basis for extrapolation of conclusions from site-specific field measurements to larger areas. Groundwater flow and solute transport models can range from simple to complex. Simple analytical calculations, such as velocity calculations based on Darcy's Law, yield first-approximation estimates of flow and transport of dissolved contaminants through aquitards. In many cases, much more sophisticated approaches are warranted, including simulations of dissolved contaminant transport with influences of diffusion, sorption and degradation through fractured materials. The current state of the science does not provide for simulations of virus or DNAPL migration through fractured aquitards.

As a result of the field work conducted during this project, we reached two important conclusions about evaluating contaminant transport through aquitards. An aquitard defined as a single lithologic unit may in fact consist of more than one hydrofacies. The practical implication of this finding is that the site-specific thickness of the aquitard and the variation in hydraulic head with depth *within* the aquitard must be determined to characterize the vulnerability of a well completed in the underlying aquifer to contamination.

The second conclusion regards the detection of human enteric viruses in groundwater from two high-capacity municipal wells. Both wells are about seven hundred feet deep and presumably produce groundwater from a confined aquifer. The presence of viruses in groundwater pumped from these wells indicates that there are rapid transport pathways through or around the overlying aquitard. This finding demonstrates that wells constructed according to accepted codes and practice, and cased through overlying aquitards, can be vulnerable to contamination by pathogens.

CHAPTER 1
INTRODUCTION

BACKGROUND

Aquitards are geologic deposits with low hydraulic conductivity (K) that can be relatively extensive and thick. Aquitards restrict the flow of groundwater to adjacent, high-conductivity formations that form *aquifers,* and aquitards can help protect adjacent aquifers from contamination. The presence or absence of an aquitard and the degree to which it restricts flow to adjacent aquifers is critical to evaluating the susceptibility of the aquifer to various contaminants.

This guidance document is intended for use by municipal water system managers, their technical consultants, and others who need to understand how aquitards influence the rate and direction of groundwater flow, and the vulnerability of wells and aquifers to contamination. Water supply system managers often face complex technical problems in relation to managing groundwater wells and well fields. The manager of a groundwater system may need to:

- Address the detection of a contaminant in a production well
- Assess the need to remediate a contaminant plume or chemical source area near a well field
- Increase or decrease production rates in existing wells to meet changes in demand
- Address concerns about the effect of pumping on nearby wells, springs, streams or lakes
- Address concerns about drawdown of water levels in an aquifer
- Develop a wellhead protection plan
- Site, design and install new production wells

To meet these challenges efficiently and cost-effectively, the manager must have adequate technical information about the *aquifer* (note – words in *italics* are defined in the Glossary of this report). In most hydrogeologic settings, the water pumped from a well is a blend of waters that has reached the well by traveling along a variety of pathways through the *groundwater flow system*. At the geographic scale typically of concern for municipal well fields, the flow system probably includes several geologic formations arranged in a stacked series of high-water-yield *aquifers* and low-water-yield *aquitards* (Figure 1.1).

A large number of factors determine the origin of the groundwater that reaches a particular well. As illustrated in Figure 1.1, these factors include the depth, thickness, and extent of aquitards and aquifers, the total depth and cased depth of each well, the natural direction of groundwater flow through the subsurface, and the changes in flowpaths due to pumping from wells. At a much smaller scale, a single well may be affected by contaminant transport through a relatively small, local feature within the flow system, such as a *fracture* through the aquitard or inadequately grouted well casing. The water supply manager informed about the regional-scale hydrogeologic setting and the site-specific conditions that impact a particular well will have a greater ability to plan and implement strategies to minimize the risk of pumping contaminated groundwater.

PURPOSE

The purpose of this report is to provide those in the water supply industry and their consultants with strategies and methods to assess the protection offered by an aquitard to the groundwater quality in an underlying aquifer. Managing a groundwater resource with a thorough understanding of the hydrogeologic system ultimately saves money. Although decisions are often driven by short-term economic considerations, the cost of bringing a new well into production can be large (on the order of several hundred thousand to tens of millions of dollars) relative to the cost of groundwater contamination investigations (tens of thousands to several million dollars). Large savings can be realized by minimizing the potential for contamination in existing wells. Anticipating where and when contamination may arrive at a well allows for adequate contingency plans and helps to avoid decision-making in response to crisis situations. In spite of the importance of aquitards in providing water quality protection for groundwater supplies, the flow and chemical transport properties of aquitards are not generally well understood. While practitioners may be frustrated by the degree of uncertainty typically remaining following a phase of hydrogeologic investigation, careful planning for, and collection of, field measurements may reduce this uncertainty. This report addresses the advantages of acquiring a good understanding of the role of an aquitard in the groundwater flow system and the uncertainty that may remain following phases of technical investigation.

HOW TO USE THIS DOCUMENT

This report summarizes methods and techniques for evaluation of aquitards. The remainder of chapter 1 discusses an overall strategy for developing and testing conceptual models of an aquitard within the context of aquifer susceptibility to contamination. Tables 1.1 through 1.5 list references to the techniques discussed in later parts of the document. Chapter 2 provides background information about contaminant transport pathways in aquitards and considerations of contaminant type. Chapters 3 through 9 summarize a series of proven methodologies and techniques for geologic characterization (chapter 3), drilling methods (chapter 4), borehole geophysical and visualization techniques (chapter 5), conducting hydraulic tests and collecting samples from open boreholes (chapter 6), and using boreholes to adequately monitor an aquitard (chapter 7). Subsequent chapters present methods to estimate vertical hydraulic conductivity (K_v) of an aquitard (chapter 8), assess groundwater quality and transport characteristics (chapter 9), and integrate various data sets to draw conclusions at various spatial scales (chapter 10). The methods are illustrated with references from the literature and, where appropriate, examples from field sites near Madison, Wis. (described in Appendix A).

METHOD OF INVESTIGATION

Aquitards should be evaluated with a specific goal or problem in mind, such as those listed at the beginning of this chapter. Figure 1.2 and Tables 1.1 through 1.5 present a series of questions and conditions that are pertinent to investigations involving aquitards. These questions and conditions are intended to guide the practitioner through an organized investigation with the goal of acquiring maximum information for minimal cost.

Each question in Figure 1.2 references one of the following tables in which a range of conditions is defined. Each table lists features of aquitards that determine the protection from contamination provided to nearby aquifers and wells. The arrows across the top of each table show, for the relevant characteristic, the continuum of possibilities from little protection (high aquifer vulnerability) to high protection (low aquifer vulnerability). References are provided to the relevant chapters of this report.

These questions and tables suggest a step-wise process to frame an aquitard investigation. The process involves developing *conceptual models* of geology, groundwater flow, and contaminant transport within the system of interest. Key components of these models include the geologic and hydrogeologic settings; contaminant migration pathways and attenuation are likely the ultimate focus. The step-wise process includes a data collection effort aimed at refining these conceptual models and yielding progressively more detailed or precise answers to questions of interest. Understanding the groundwater flow system is essential to assessing the vulnerability of the system to contamination. The methods described in this report can be applied to a variety of groundwater-related problems; we emphasize their application to assess aquitard protection from contamination. The importance of conceptual models in this effort is further addressed below.

Table 1.1 Aquitard presence or absence (chapter numbers reference discussion within this report)

Less protection	**Known presence or absence of aquitard**	**More protection**
	⟵⟶	
aquitard absent	suspected aquitard or aquitard characteristics uncertain	confirmed aquitard
small (feet)	lateral extent (Chapter 3)	large (miles)
thin (inches)	thickness (Chapter 3)	thick (10's of feet)
discontinuous (interbedded sands or permeable zones, erosional *windows*)	continuity (Chapter 3)	continuous (no breaks or *windows*)

Table 1.2 Groundwater flow system

Less protection	Characteristics of groundwater flow system and well field	More protection
	⟵⟶	
short (feet)	length of *flow path* (Chapter 3)	long (100's of feet)
short (days)	*travel time* (Chapters 9 and 10)	long (decades)
high	*flux* across aquitard (Chapters 9 and 10)	low
short (feet)	distance to aquitard edge	long (miles)
toward well	ambient groundwater flow direction	away from well
many sources	contaminant source presence	few or no sources
many	*multi aquifer wells*	none
many	poorly sealed well casings	none

Table 1.3 Physical Properties of aquitard

Less protection	Aquitard properties	More protection
	⟵⟶	
higher (K>0.1 ft/day)	*hydraulic conductivity* (Chapters 5 through 8)	lower (*K*<.001 ft/day)
many connected *fractures*	*fractures* (Chapters 4 through 7)	few *fractures*
non-*retarding*	chemical properties (Chapter 9)	*retarding*

Table 1.4 Detection of fractures in aquitard

higher probability of fractures	Field observation	lower probability of fractures
	⟵⟶	
thin (0-50 ft)	aquitard thickness (Chapter 3)	thick (50 – 100s of ft)
many visible fractures	visible fractures in cores, boreholes, or outcrop (Chapters 4, 5)	few or no visible fractures
matrix is non-plastic	*plasticity* (Chapter 5)	matrix is highly plastic
field values higher than lab values	aquitard field vs. laboratory hydraulic conductivity (Chapters 5, 6 and 8)	field and lab values about the same
response to pumping or recharge	response in piezometer in aquitard to external stress (Chapter 8)	little response to pumping or recharge
low (<1)	vertical hydraulic gradient within or across aquitard (Chapters 6 and 7)	high (>1)
deep penetration (many feet)	penetration of tracers (isotopes, chloride, contaminants) into aquitard (Chapter 9)	little penetration (< a few feet)
significant variation	spatial variation within or across aquitard in piezometric head and chemistry (Chapters 7 and 9)	little variation

Table 1.5 Contaminant characteristics

Less protection	Contaminant characteristics (Chapter 2)	More protection
	⟵⟶	
DNAPL, *particulates*	type of contaminant	*solutes*
heavier than water (*DNAPL*)	specific gravity	lighter than water (*LNAPL*)
low (nitrates)	*sorption* by aquitard materials	high (*metals*)
high (*metals, viruses*)	toxicity	low (sulfate, chloride)

NATURE AND ROLE OF CONCEPTUAL MODELS

This document describes many methods and techniques available for use in assessments of contaminant migration through aquitards and provides a broad framework for applying them. This framework is based on the premise that the decisions to acquire the various types of information and the development of data interpretations be founded on *conceptual models* for the conditions in the investigation area. Water management decisions/planning should be founded on the model(s) but with clear recognition of the uncertainties associated with them. This document also advocates use of mathematical models in aquitard assessments because such models are the basis for quantification of groundwater flow and contaminant migration. Mathematical models provide insight about potential future events and the probability of aquifer or well contamination. However, when mathematical models are applied, they are always founded on a conceptual model. If the conceptual model is weak or wrong, the output of the mathematical model is not reliable and may be misleading. U.S. EPA (1993) provides the following description of the nature and role of a conceptual site model in the context of groundwater restoration in the Superfund Program. This description is sufficiently general to be appropriate for aquitard assessments.

"The site conceptual model typically is presented as a summary or specific component of a site investigation report. The model is based on, and should be supported by, interpretive graphics, reduced and analyzed data, subsurface investigation logs, and other pertinent characterization information. The site conceptual model is not a mathematical or computer model, although these may be used to assist in developing and testing the validity of a conceptual model or evaluating the restoration potential of the site. The conceptual model, like any theory or hypothesis, is a dynamic tool that should be tested and refined throughout the life of the project …the model should evolve in stages as information is gathered during the various phases of site remediation. This iterative process allows data collection efforts to be designed so that key model hypotheses may be tested and revised to reflect new information."

This guidance document presents methods that pertain to the three main components of aquitard assessment: (i) aquitard geology (e.g. lithology, stratigraphy); (ii) the groundwater flow system and (iii) contaminant migration. The starting point for aquitard assessment involves focus on geology. With geologic information as the framework, consideration can then be directed at groundwater flow. Finally, contaminant migration can be evaluated within the context of groundwater flow and pathways analysis. An overall goal is to develop a reliable conceptual model for contaminant migration that includes specification of most likely pathways and contaminant attenuation processes suitable for quantitative analysis using mathematical models. An important aspect of aquitard assessment is identification of multiple hypotheses or models for the hydrogeologic conditions at the beginning stage of the project and proceeding with data acquisition to eliminate hypotheses as progress is made. If the site information is insufficient to narrow the possibilities down to a single conceptual model, several models or hypotheses should be kept in play to elucidate uncertainties inherent in the aquitard assessment.

In the development of the geologic conceptual model, the aquitard(s) is identified and delineated primarily using geologic methods such as core logs, surface and borehole geophysics and stratigraphic considerations. Appendix B provides our geologic conceptual model for the Eau Claire aquitard, a regionally extensive bedrock aquitard that overlies the primary aquifer used for water supply in Madison, Wis.

In the development of the conceptual model for the groundwater flow system, the thickness and areal extent of the aquitard may change from that deduced from the geologic analysis. Hydraulic properties can vary within a geologically-defined lithofacies and depending on the scale of interest, several *hydrofacies* may be defined within a stratigraphic unit. With respect to aquitards, hydraulic head or K data may show that the extent of the low-K portion of a geologic unit differs from established geologic boundaries. For example, a geologic unit dominated by a shale facies may offer the hydraulic protection of an aquitard within only part of its thickness (e.g. Appendix A, Figure A.5). The K_v within an aquitard that is initially identified based on geologic or geophysical evidence may vary vertically across the unit by several orders of magnitude (e.g. 10^{-2} to 10^{-5} ft/day) with the most effective portion of the aquitard being at the lower part of the K_v range. A 30-ft thick geologic unit initially identified as the aquitard could be re-defined as a 3-ft thick aquitard once hydrogeologic considerations are taken into account. Our conceptual model of the groundwater flow system in Dane County, Wis. demonstrates this principle: we refined our model based on hydraulic data collected from within the Eau Claire aquitard at the Nine Springs field site (Appendix B).

The geologic and groundwater flow conceptual models serve as the starting point for the conceptual model for contaminant migration. The spatial distributions of contaminant types and transport pathways are emphasized in this conceptual model. The major issue at this stage is assessment of potential preferential pathways for contaminant migration, such as fractures. The aquitard may have an extremely low bulk vertical hydraulic conductivity (K_{bv}) (e.g. $K_{bv} \approx 10^{-4}$ to 10^{-5} ft/day) and yet have open, through-going vertical fractures that provide rapid, direct pathways for some types of contaminants such as particulates or DNAPLs (this is considered in more detail in *Contaminant Transport Through Aquitards: A State-of-the-Science Review*. We present a conceptual model of contaminant transport across the Eau Claire aquitard in Appendix B to this report.

Although this document advocates the use of mathematical models in aquitard assessments, we should keep in mind that the mathematical model results depend entirely on the conceptual model. Bredehoeft (2005) conducted an analysis of 21 major groundwater investigations in which numerical models were used to make predictions. He compared these predictions to the actual outcomes at these sites years or decades later and concluded:

"*The foundation of model analysis is the conceptual model. Surprise is defined as new data that renders the prevailing conceptual model invalid; as defined here it represents a paradigm shift. Limited empirical data indicate that surprises occur in 20-30% of model analyses. These data suggest that groundwater analysts have difficulty selecting the appropriate conceptual model. There is no ready remedy to the conceptual model problem other than (1) to collect as much data as is feasible, using all applicable methods – a complementary data collection methodology can lead to new information that changes the prevailing conceptual model, and (2) for the analyst to remain open to the fact that the conceptual model can change dramatically as more information is collected. In the final analysis, the hydrogeologist makes a subjective decision on the appropriate conceptual model*."

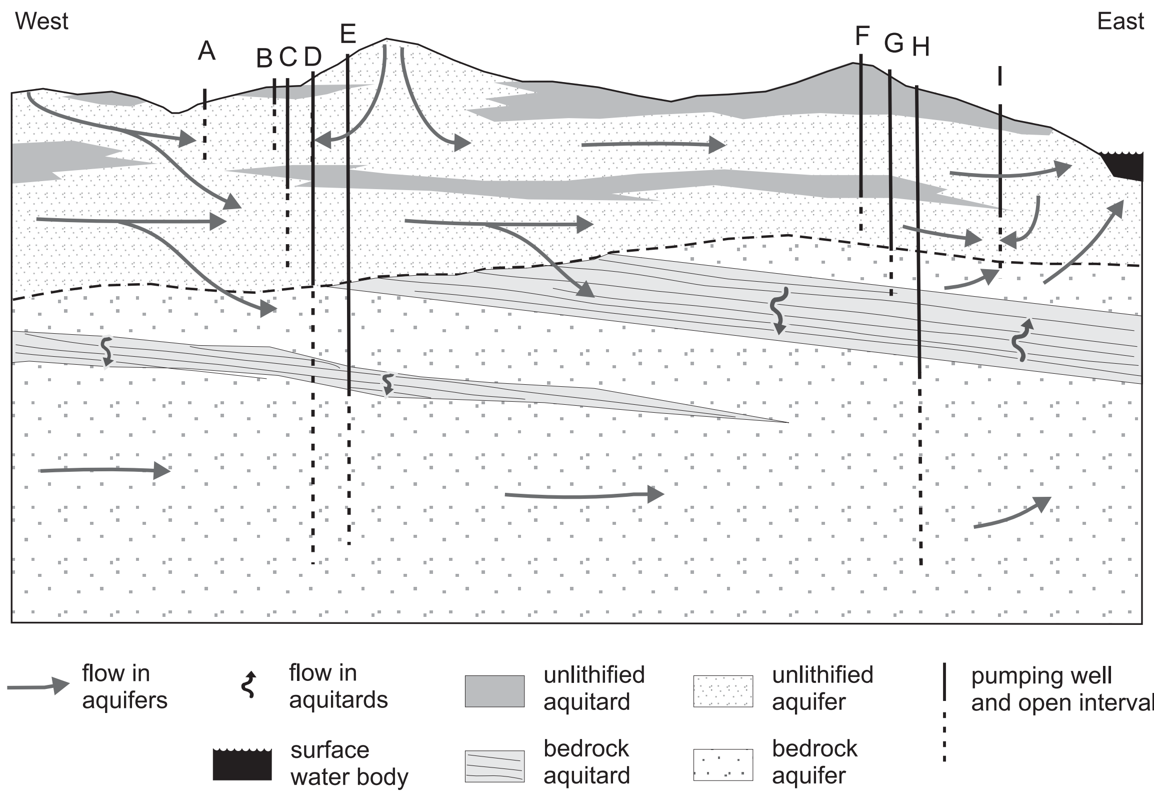


Figure 1.1 Flow paths to pumping wells in a complex geologic setting.

Is there an aquitard present? (Table 1.1)

⇩

How do the aquitard and the well or area of interest fit into the groundwater flow system? (Table 1.2)

⇩

What are the physical, chemical, and hydraulic properties of the aquitard? (Table 1.3)

⇩

Is the aquitard likely to be fractured? (Table 1.4)

⇩

To what degree will contaminants of concern be retarded or attenuated in the aquitard? (Table 1.5)

Figure 1.2 Sequence of questions in characterizing protection from an aquitard

CHAPTER 2
FACTORS IN AQUITARD VULNERABILITY

This chapter provides a brief overview of the geologic, hydraulic, and contaminant properties that affect flow and chemical transport between aquitards and aquifers. *Contaminant Transport Through Aquitards: A State-of-the-Science Review*, the companion report to this technical guidance, includes a detailed review of these topics and relevant examples from the scientific literature.

TYPES OF AQUITARDS

Aquitards typically consist of *unlithified*, fine-grained sediments such as clay and silt, or *lithified*, low-*permeability* rock formations, such as shale or mudstone. Unlithified aquitards are often the focus of hydrogeologic investigations at contamination sites, because they are usually encountered at shallow depths. Bedrock aquitards may be positioned deeper in the subsurface, where they are more likely to effect regional groundwater flow systems.

Very few aquitards are geologically *homogeneous*; most aquitards contain sediment or rock of various *lithologies.* For example, aquitards may be composed of layers of clay interbedded with sand and gravel lenses, or layers of shale or siltstone interbedded with sandstone layers. Although aquitards are often lithologically *heterogeneous*, they yield relatively small volumes of groundwater and impede groundwater flow to aquifers. Geologically heterogeneous aquitards may be treated as a single hydrogeologic unit in the analysis of the regional flow system or for the purposes of well design and construction. However, the specific effects of these heterogeneities must be evaluated when contaminant migration is of interest.

Another significant characteristic of aquitards is the occurrence of *fractures*. Fractures are critical to the risk of contaminant transport to a well because through-going fractures can act as a preferential pathway, providing rapid transport of contaminants through an otherwise low-permeability formation.

SUSCEPTIBILITY OF REGIONAL AQUIFERS AND WELLS

Aquitards generally restrict groundwater flow, but no geologic formations are completely impermeable; some groundwater flows across even the lowest conductivity aquitards. Aquitards decrease the susceptibility of aquifers and wells to contamination by increasing both the time of travel and the flow path length from a contaminant source. Long travel times to a well may be associated with increases in dilution, retardation and degradation of groundwater contaminants. An unfractured, clayey aquitard only tens of feet thick can cause delays of up to thousands of years, but the transport time scale may be reduced to years or less if substantial, through-going fractures exist.

When siting a new well, system managers are likely constrained by several very practical considerations, such as locating the well in proximity to the area of water demand, or the acquisition cost of a particular land parcel. The total and cased depth of a new well may be constrained by cost, or by the well yield necessary to meet demand. However, if the long-term preservation of high quality groundwater is of concern, the relationship of the site and well design to the hydrogeologic setting is of primary importance. Figure 1.1 illustrates the significance of well location and design relative to the groundwater flowpaths in a complex (but realistic) hydrogeologic setting. In Figure 1.1, well A receives some groundwater from the west, but also receives a portion of its flow directly from recharge from the near-by land surface. Because well A is completed in a surficial aquifer with no overlying aquitard, it is extremely susceptible to contamination. Well B is less susceptible because it is cased through a surficial aquitard, and the flow paths to the well (from the east) are longer, providing more distance (and therefore, more time) for contamination to dissipate along the flow path. Although located close to well B, well C is drilled and cased deeper in the flow system. Groundwater pumped from well C originates from a different source area than that pumped from well B, and may be of a very different quality.

Flowpaths can diverge around the edge of the aquitard, providing recharge to the underlying aquifer. The resulting flow path from the surface to the deeper system provides a route of contaminant migration around the edge of the aquitard to the deeper aquifer. As illustrated in Figure 1.1, although well D is cased into the bedrock formation, the upper, uncased portion of the well receives groundwater from the same region as well C, which is open to the unlithified aquifer only. Well D is also open to the deeper bedrock aquifer, resulting in a blend of waters from the upper unlithified formations and the very deep flow system. The water quality at wells C and D may be very different due to this blending. Wells D and E may cost significantly more money to drill and construct than wells A, B and C, but may have very different groundwater quality than the shallower wells. Wells D and E are less susceptible to contamination than wells A, B and C. Well E receives the maximum protection possible from overlying aquitards. It is significantly less susceptible to contamination than well D because the additional casing depth restricts flow from the upper portions of the system.

The time of travel through or around aquitards can range from less than a year to thousands of years, depending on the type of contaminant pathway present and the hydraulic properties of the system. The time of travel of groundwater to a pumping well is a function of the well's position in the flow field relative to an aquitard, as illustrated in Figure 2.1. In the absence of an overlying aquitard, there is a rapid time of travel from the ground surface to a pumping well completed in an unconfined aquifer and the well is very susceptible to contamination (Figure 2.1a).

Figure 2.1b illustrates a well completed below a fractured aquitard. In this case, only a small volume of water may travel through the aquitard along the preferential pathway (the fracture), but the time of travel to the well is very rapid. Several factors will determine if the aquitard, although fractured, provides adequate protection for the well. These include the contaminant concentration migrating through the fracture, the concentration of the contaminant that is of regulatory concern, and the degree of dilution provided from mixing with groundwater from other flow paths to the well.

Figure 2.1c illustrates a third case, wherein contaminated water reaches the well via a relatively long flow path around the edge of the aquitard. In this case, the longer time of groundwater travel to the well may favor attenuation of contaminant concentrations by processes such as *dilution*, and chemical or biological *degradation*.

Pumping from wells can reverse the direction of hydraulic gradients and flow within the groundwater system, and thereby decrease the natural protection afforded by an overlying aquitard. As illustrated in Figure 1.1 at wells F, G, H and I, vertical gradients near a regional discharge area will be upwards from an underlying aquifer to a surface water body. However, pumping from a deep aquifer can reverse the natural gradient across an aquitard, promoting contaminant migration through fractures or windows in the aquitard. Well F is located relatively far west of the eastern edge of the lower unlithified aquitard. Under natural conditions well F receives all of its flow from the west, and is more susceptible to contamination than well I. If the drawdown in groundwater levels is large due to pumping from well I, the natural upward direction of groundwater flow may be reversed near the well. In this case, well I may receive some groundwater from the east and is more susceptible than well F to surface contamination via flow around the eastern edge of the aquitard. Well H would be more expensive to construct but vulnerability to contamination would be minimized. The well yield of well H may be significantly different than wells F, G, and I, depending on the transmissivities of the aquifers.

TRANSPORT PATHWAYS

Discrete pathways for groundwater flow and contaminant transport across aquitards are common in many settings. These include fractures and *macropores,* or large openings, caused by tree roots or burrowing animals. Human-constructed pathways such as uncased or abandoned wells, or wells constructed with an ineffective seal between the well casing and borehole wall, also provide pathways across aquitards.

Windows

Geologic processes that occurred tens of thousands of years ago may result in high-permeability *windows* within an aquitard. For example, laterally extensive deposits of low permeability glacial till or lake sediments often contain discontinuous lenses of sand and gravel. Erosional processes may result in large-scale removal of, or incision through, an otherwise extensive aquitard. Understanding the geologic history of a region provides insight into the likelihood of windows or preferential flowpaths in the aquitard.

Fractures and sink holes

Here, we use the term "fracture" to refer to an open feature that allows water flow. Many other fractures may exist that are closed. Fractures form due to imposed stresses at some point in geologic time, and they may be open or closed at the present time depending on geologic conditions subsequent to their formation.

Several processes cause fractures in fine-grained unlithified aquitards. Unsaturated aquitards with lower clay content are particularly susceptible to extensive fracturing by geologic stresses or deformation. Where unlithified aquitards are subject to weathering, shrinking and drying of the sediments can cause fractures to form, particularly in the unsaturated zone above the water table. The density of fractures in these settings typically decreases significantly with depth below the weathered portion of the aquitard, but fractures can extend to depths on the order of 30 to 150 ft below the water table. Deposits with higher percentages of clay may be relatively plastic. The plasticity can promote fracture closure at depth, at some later time, if sand or silt has not been washed into the fracture.

In some near-surface settings, aquitards consisting of relatively soluble carbonate rock, such as limestone, are vulnerable to the formation of *karst* features. *Karst* terrain is characterized by fractures, caves and sinkholes that may breach the integrity of the aquitard.

Multi-aquifer wells

Some relatively deep water supply wells and other subsurface borings are constructed with an open, un-cased borehole across more than one aquifer. This design may maximize well yield and minimize the cost of casing material, but it can create a pathway for contaminant transport across an aquitard. The borehole of these multi-aquifer wells provides a "short circuit" across an aquitard that would otherwise restrict the hydraulic connection between overlying and underlying aquifers. A borehole open to two aquifers is a transport pathway when the head in the upper aquifer is greater than the head in the lower aquifer, inducing flow from the upper to the lower aquifer (Figure 2.2).

Relatively few multi-aquifer wells are required to significantly increase the effective K_v of an aquitard. For example, Hart and Bradbury (2006) estimated the volume of flow through an open-borehole well in Wisconsin to be 2.6×10^5 gallons/day (1000 m^3/day). Very rapid transport of contaminants to the underlying aquifer can occur in these boreholes, across an otherwise protective aquitard. Similar to a poorly grouted well casing, this preferential pathway provides an opening that can facilitate transport of *particulate* and *aqueous* contaminants.

CONTAMINANT TYPES

Three general types of contaminants in groundwater include aqueous contaminants (those that are dissolved in water), non-aqueous phase liquid (NAPL, typically petroleum products or chlorinated solvents) and particulate matter (*colloidal* size particles that may be inert or biologically active). The fate and transport behaviour of each type of contaminant in a groundwater system depends on their respective chemical properties, such as their density, solubility, or reactivity. There is also considerable variability in the concentration at which various types of contaminants pose significant threats to human health (for example, the drinking water maximum concentration limit (MCL) for nitrate is 10 parts per million, while the MCL for carbon tetrachloride is 5 parts per billion).

Aqueous Contaminants

Aqueous contaminants include inorganic major ions (e.g. sulfate and chloride), nutrients (e.g. nitrate and phosphate), trace elements (e.g. chromium, arsenic, and lead) and dissolved portions of organic contaminants (e.g. trichloroethylene (TCE), benzene). Aqueous contaminants are transported along with the *advective* flow of groundwater, following groundwater flow paths governed by the hydrologic system. Some aqueous phase contaminants, such as chloride, are non-reactive, meaning that they do not degrade as they are transported in the groundwater system. As non-reactive contaminants migrate, their concentrations are influenced only by flow (*advection*) and *dilution* due to mixing (molecular diffusion and/or mechanical dispersion).

Some aqueous contaminants tend to sorb onto geologic sediments. *Sorption* does not reduce the total chemical mass in the hydrogeologic system, but it does delay ("*retard*") the transport of contaminant mass through the groundwater flow system. Examples of contaminants strongly influenced by sorption are lead and the soluble portion of polychlorinated biphenyls (PCBs).

Some aqueous contaminants are subject to biological, chemical or radioactive *degradation* in the groundwater system. These processes result in chemical transformations that can reduce the overall contaminant mass in, and retard the rate of migration through, the flow system. A contaminant may degrade to a product that is also a contaminant, such as when TCE transforms to cis, 1,1 dichloroethylene or vinyl chloride. In this case, the degradation of TCE may, overall, cause an increase in the severity of the groundwater contamination.

NAPLs

NAPLs include liquids that are less dense than water (light non-aqueous phase liquids (LNAPLs), such as gasoline and fuel oil) and those that are denser than water (dense non-aqueous phase liquids (DNAPLs), such as chlorinated solvents, creosote and PCB liquids). NAPLs move through the subsurface under the influence of their density, which can lead to the migration of the liquid product in directions different from groundwater flow.

Due to their higher density, DNAPLs have the greatest propensity to migrate through fractured aquitards. Typical chlorinated solvent DNAPLs readily flow downward through small fractures, including fractures so small that they cause the K_{bv} to be only slightly (and often imperceptibly) larger than unfractured conditions. If aquitards have preferential pathways such as through-going networks of fractures, DNAPLs may migrate downward through the aquitard even where groundwater hydraulic gradients are upward.

In very low-permeability unfractured aquitards, aqueous contaminants can move by molecular diffusion downward even if the groundwater gradients are upward, but, the downward migration may be very limited. In an area of upward hydraulic gradients across an aquitard, these gradients would prevent particulate contaminants from being transported downward. In this case, the aquitard would have generally good integrity with respect to particulate and aqueous contaminants, but could have poor integrity for DNAPLs.

Within the class of NAPLS, there are extreme differences in subsurface behaviour due to differing degrees of solubility, sorption and reactivity. For example, TCE poses a much greater potential to cause widespread groundwater contamination than PCBs because TCE is moderately soluble in water and PCBs are nearly insoluble relative to their MCLs. Also, TCE is much less strongly sorbed to aquifer and aquitard solids than PCBs. Dissolved TCE can be transported large distances relatively quickly by groundwater flow, and this is the primary reason why TCE is commonly found in groundwater and PCBs are not.

NAPL contaminants are present in the aqueous phase, as well as the undissolved ("product") phase, because all NAPLs are soluble in water to some degree. Solubilized portions of NAPL contaminants behave similarly to other aqueous contamination in that they are transported by the flow of groundwater.

Particulates

Particulate contaminants include extremely small, *colloidal*-sized particles occurring in two categories. The first is comprised of mineral matter or organic matter typically derived from plants, wood or coal. These particles are usually not contaminants on their own, however, they may cause contaminant migration by carrying attached (sorbed) contaminants. For example, a mobile colloid composed of mineral matter may carry sorbed molecules of hazardous metals such as cadmium. A second category of particulate contaminants includes bacteria and viruses, which are biologically active. The potential for transport of bacteria and viruses across aquitards is reviewed in the companion report, *Contaminant Transport Through Aquitards: A State-of-the-Science Review*. We have included much of this review and specific references here, because this material is not widely disseminated amongst hydrogeologists and water supply engineers. Viruses have been detected in groundwater at depths up to 67 meters (Keswick and Gerba 1980), and they have been reported to move laterally as far as 408 m in glacial till and 1600 m in fractured limestone (Keswick and Gerba 1980; Robertson and Edberg 1997). Transport of viruses through aquifers is further evidenced by their widespread occurrence in drinking water wells (Gerba and Rose 1990). In one study of 448 groundwater sites in 35 states, 141 sites (31.5%) were positive for at least one virus type (Abbaszadegan et al. 2003).

Particulate contaminants are transported in the same general manner as aqueous contaminants, along with the advective flow of groundwater. However, transport of particulates may be limited by filtration at small pore sizes between mineral grains in rock or sediments, or by sorption to rock or sediments.

Some features in the subsurface, such as fractures and root holes in clayey aquitards, may be large enough to facilitate the transport of viruses into underlying aquifers. Viruses can pass through fractured clay till in openings as small as 3 to 5 microns. Preferential flow along fractures or other pathways results in colloids moving substantially faster than aqueous contaminants. Several studies have documented virus transport through clay fractures at velocities ranging from 2 to 360 meters/day (McKay et al. 1993, Hinsby et al. 1996). Poorly grouted well casings may also provide a preferential pathway for viruses to reach an aquifer.

In order for a well to become virus contaminated there must be a fecal source nearby. Leaking sanitary sewer lines, septic systems, landfills, field-applied sludge or septage, effluent holding ponds, wastewater infiltration or irrigation facilities, and surface waters that recharge groundwater, are potential sources of viruses to the groundwater system.

The greater the fecal loading onto or into the ground the greater the opportunity for the underlying groundwater to become virus contaminated. A well located in the middle of a large city underlain with leaking sanitary sewers stands a greater chance of becoming pathogen contaminated than a well adjacent to a few septic systems. Intuitively, the greater the level of fecal loading near the ground surface, the greater the level of viruses reaching the upper boundary of an aquitard, and the greater the opportunity for viral movement through the aquitard.

Preventing virus contamination of a confined aquifer begins with decreasing fecal loading above the aquifer and increasing the distance from a fecal source to a drinking water well. There are many uncertainties in predicting viral transport, so determining an effective distance between a fecal source and a well drawing from an unconfined aquifer is largely educated guesswork. Consideration of an aquitard, for which there is even less virus transport information, in determining the appropriate setback distance between fecal source and a well completed in a confined aquifer, is more uncertain. The presence of an aquitard should increase protection from viruses for properly constructed wells. Viruses were detected in samples collected from wells completed in a confined aquifer during field studies conducted as a part of this research project (Borchardt et al., in review; Chapter 9).

For people to become virally infected from drinking contaminated groundwater not only do the viruses need to be transported to the well, they must also survive the transport process and remain infectious. Treatment systems at the wellhead, such as disinfection, may inactivate viruses. The most important determinant of virus inactivation in groundwater is temperature, as temperature increases so does the inactivation rate (Hurst et al. 1980, Yates et al. 1985, Yates and Yates 1988). Therefore, confined aquifers in arid regions with warm groundwater temperatures (e.g. 20°C) may be less prone to contamination with infectious viruses. The travel time for a virus to reach a well is also an important factor. If the travel time is greater than the virus survival time, it is unlikely that a virus reaching the well would be infectious. Although the upper limit for survival time in groundwater has not been determined for many viruses, water that has a travel time to a pumping well on the order of a year would be more likely to transport an infectious virus than waters with travel times on the order of 10 to 100 years.

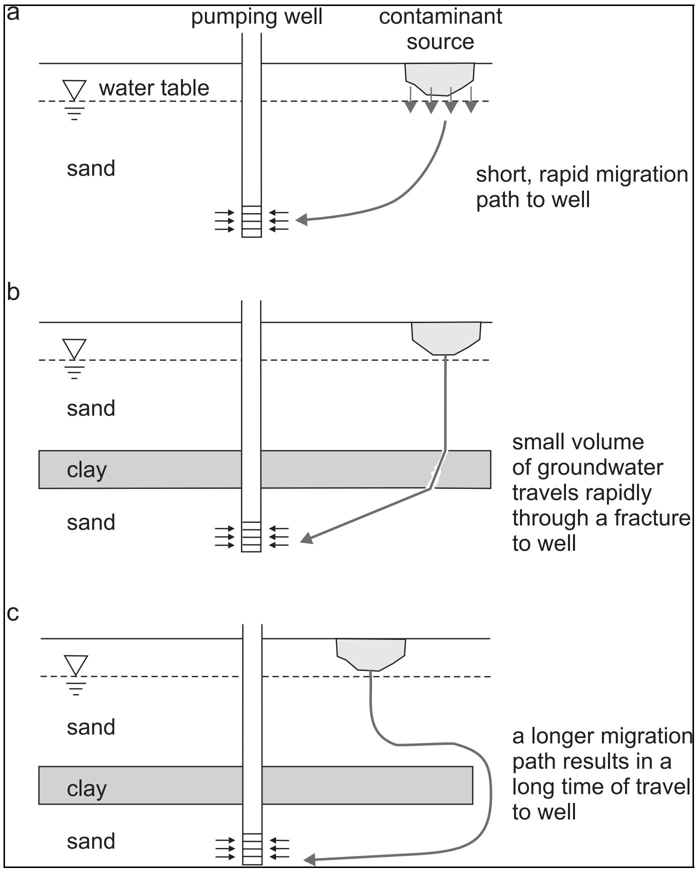


Figure 2.1. Travel times and flowpaths to a pumping well.

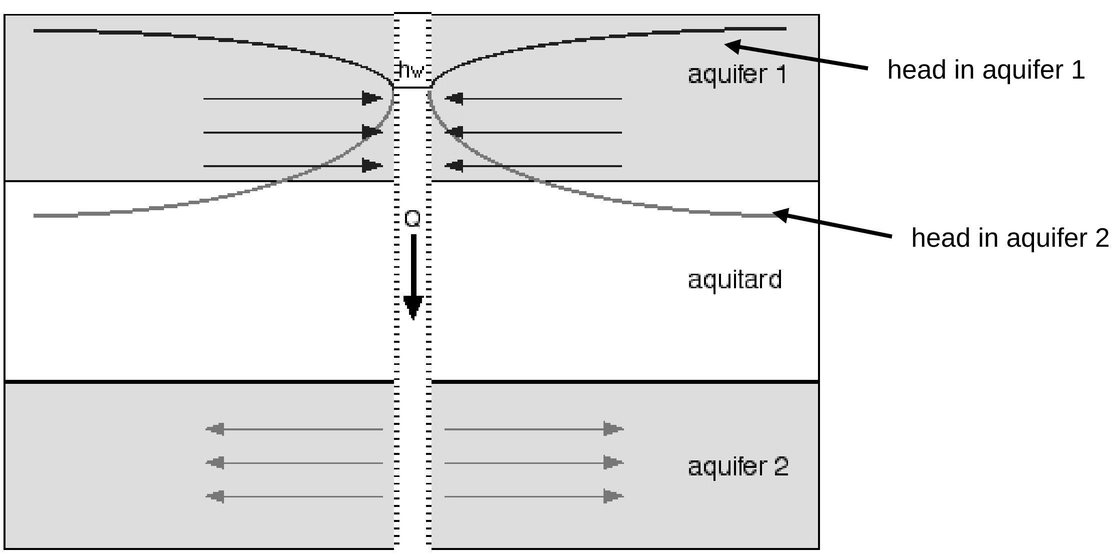


Figure 2.2 Flow across aquitard through a multi-aquifer well. Arrows show direction of groundwater flow to and from the well. h_w indicates the water level in the well, Q represents direction of flow within the borehole.

CHAPTER 3
STRATIGRAPHY AND LITHOLOGY: DETERMINING THE PRESENCE AND EXTENT OF AQUITARDS

The first step in aquitard characterization is to determine whether an aquitard is present within the groundwater system, and, if present, to determine its lateral and vertical extent within the regional hydrogeologic setting. Compiling information and data at the regional scale allows one to formulate a conceptual model of the extent of protective aquitards and the probability of windows or large discontinuities existing within the aquitards. Knowledge of the layering and lateral variability in aquitard and aquifer formations is critical to wellhead protection efforts, developing a cost-effective response to contamination, and to site and construct new wells in a manner that maintains high groundwater quality.

This chapter describes regional mapping and geophysical techniques useful to evaluate the regional extent of aquitards. The mapping is intended to be relatively inexpensive, because it relies primarily on data that may be obtained from local regulatory agencies or state geological surveys. For a listing of state geological surveys, or their equivalent agencies, see the American Association of State Geologists web site at http://www.kgs.ukans.edu/AASG/AASG.html.

While our general strategy to assess aquitard integrity is the same for *unlithified* and *lithified* aquitards, many of the investigative tools used in these settings differ due to the nature of drilling and borehole conditions in sediments versus rock. The cost per foot for drilling in rock is generally much higher than for drilling in clayey aquitards; the geophysical and hydrophysical methods described in this and subsequent chapters are primarily used in lithified aquitards as an alternative to installing a dense network of deep monitoring wells. There is a substantial scientific and engineering literature describing field investigations and mathematical modeling focused on unlithified aquitards (see *Contaminant Transport Through Aquitards: A State-of-the-Science Review*). In contrast, the literature concerning lithified aquitards (e.g. shale, siltstone, minimally fractured carbonate rock) is sparse. Potter et al. (2005) provide an excellent general reference describing the origin and characteristics of mud and mudstones, encompassing the lithologies of most unlithified and lithified aquitards.

REGIONAL MAPPING OF AQUITARDS WITH LITHOLOGIC LOGS

Relevant hydrogeologic setting

A map of a hydrogeologic unit can be constructed for any setting if the unit is clearly defined and geologic or *lithologic* logs are available at a sufficient density.

Methods of construction

Maps of aquitard thickness and extent may be compiled from drilling and geologic records from any wells sufficiently deep to encounter the unit of interest (private residential and irrigation wells, municipal wells, environmental monitoring wells, etc.). Borehole geophysical logs and image logs are a useful supplement to drilling records to correlate depths and thickness of fine-grained rock or sediment across the region.

Data expected

A map of the aquitard of interest, showing thickness and extent. It is important to display the control points (that is, the locations where drill logs are available) on the map to convey the data density and distribution.

Advantages

The map may be refined and updated as additional information becomes available. It is an excellent tool for understanding variability in an aquitard across a broad geographic area.

Limitations

There may be large geographic regions where data are not available, or available information may be of inconsistent quality. One challenge is to apply a consistent set of criteria in defining the unit of interest. For example, a driller's record may describe a "gray sandstone" at a depth where a gray shale is expected. In this case, the driller's description may be a simplification of rock that a geologist would label a sandy shale.

An aquitard mapped on the basis of geologic evidence, particularly its thickness, may be only partially consistent with hydraulic head and/or K_v data acquired in later stages of investigation. Therefore, geologic mapping of the aquitard is regarded as a first-step in defining the effective thickness of an aquitard.

Cost

Cost should be relatively inexpensive, as low as a few thousand dollars, to have a consultant compile relevant information and construct a map. More may be invested in this process to construct a detailed map of an aquitard associated with a particularly valuable aquifer. Personnel at a water utility or an agency where relevant records are maintained (such as a state geological survey) may also have the technical background appropriate to compile the map.

Companion tools

Other information useful in conjunction with the map of the aquitard are maps of the potentiometric surface of the overlying and underlying aquifers. These can be used to determine recharge areas for the aquifers and to determine flow directions to wells. The information can be quantified with numerical models to estimate flux and contaminant transport rates across the aquitard, and to identify contributing areas for particular wells.

Site-specific example

A map of the shale facies of the Eau Claire Formation in Dane County, Wis. was prepared as part of a regional hydrogeologic study initiated by water utilities in the county (Figure 3.1). The map is based on records from 115 wells in or near Dane County. The shale facies thins from over 40 feet in thickness in western Dane County to areas where it is absent from the rock sequence, to the northeast. The hydrogeology of the area is described in Appendix A of this report.

Several data points that are not in good agreement with other near-by well-records have been evaluated on a case-by-case basis to generate and smooth the contours on the map. This is a challenging aspect of constructing the map, because these inconsistencies may reflect real and abrupt differences in the thickness or lithology of the shale facies. In this example, geologic logs used to compile Figure 3.1 were completed by numerous geologists and well drillers over many decades, leading to differences in identification and definition of the shale facies. Although the map yields useful insights into aquifer vulnerability at a regional scale, unless data of are very high quality and density, this exercise provides little information about local conditions that may impact a particular well. The map assesses thickness of the Eau Claire based on lithology; information provided later in this report assess the thickness of the aquitard that causes a steep hydraulic gradient between the upper and lower aquifers.

The greatest uncertainty in this map is associated with the areas underlying the lakes in central Dane County. Based on the depth of lake sediment encountered while drilling wells near the lakes, it is likely that the shale facies was eroded within the lake basins during periods of glacial advance. The hypothesis that there are windows in the shale aquitard under the lakes was supported by results of sensitivity testing with a three-dimensional groundwater flow model of Dane County (Krohelski et al. 2000).

The absence of the shale to the northeast, and windows in the shale underlying the lakes, are significant factors in assessing the protection that the aquitard provides to deep wells from some contaminant classes. Due to drawdown in water levels from pumping in the deep Mt. Simon aquifer, flow direction to wells in central Dane County is from the northeast (Figure 3.2). Combining the generalized maps of flow direction and aquitard extent implies that widespread, non-point nitrate contamination in the overlying glacial and Wonewoc aquifers (resulting from agricultural practices in rural areas of the county) may reach the Mt. Simon aquifer via recharge from the shallow system to the deep in the absence of the shale in the northeast. Wells located close to this recharge area would be more susceptible to nitrate contamination. Wells completed in the Mt. Simon aquifer in southwest Dane County appear protected by the extensive and thick shale layer. Their location west of the groundwater divide affords them additional protection from non-point groundwater contamination compared to wells east of the divide.

This regional map provides little insight into the protection afforded to the deep aquifer from DNAPL contamination. DNAPLs readily migrate through fractures, and this mapping exercise provides no assessment of fractures in the Eau Claire aquitard.

The map has implications for construction of new wells and for potential remediation of older wells. Low levels of volatile organic compounds (VOCs) were detected in a well within the City of Madison that is open to both the overlying Wonewoc aquifer, ten feet of Eau Claire shale, and the underlying Mt. Simon aquifer. The VOCs may be reaching the well through the Wonewoc aquifer, in which case extending the well casing through the shale facies may significantly improve water quality at the well. However, the well is less than 0.5 miles from the lake. If there is a window in the aquitard in the lake basin, as interpreted in Figure 3.1, then dissolved VOCs may have reached the deeper Mt. Simon aquifer via a downward flowpath near the lakes. In this case, installing a deeper casing in the well may not reduce VOC concentrations in well water.

REGIONAL MAPPING OF AQUITARDS WITH GEOPHYSICAL METHODS

Operating principle

In aquitard studies, geophysical methods are used to measure contrasts in material properties to "image" the geologic properties of the subsurface. Here, we describe data collected at or near the ground surface ("surface geophysics") and through boreholes and wells ("borehole geophysics"). There may be several differences between adjacent aquifers and aquitards that can be identified with surface and/or borehole geophysical tools. For example, aquitards generally conduct electricity more readily than aquifers, and geophysical methods that measure how well the earth conducts electricity are often useful in these settings. Another contrast in material properties that often exists between aquifers and aquitards is the propagation speed of seismic waves or vibrations; seismic waves travel more slowly in shale than sandstone.

Geophysics can be used to map the extent, depth and thickness of an aquitard (Figure 3.3). As a general rule, geophysical surveys can most readily locate the edge of aquitards. Determining the thickness and depth of aquitards is not as easily accomplished, nor is there as much certainty in the results. Surface geophysics encompasses many techniques, including ground penetrating radar, seismic methods, and electromagnetic methods. Table 3.1 lists several surface geophysical methods useful in the study of aquitards, the contrasting physical property measured, the expected information resulting from the survey, and some comments on the method. Application of these techniques to locate and delineate aquitards is not widely disseminated amongst hydrogeologists and water supply engineers. The following texts provide useful information on both the theory and practice of geophysical methods: Telford et al. (1990), Reynolds (1997), and Burger (1992).

Advantages

Geophysical methods can, in general, give more complete and less costly coverage of an aquitard than drilling alone. In many cases, surface geophysical surveys can be conducted at locations inaccessible to a conventional drill rig because the geophysical instruments are relatively light and easily transported. Geophysical data is quickly attained; a question that might takes weeks to answer by drilling might be answered in an afternoon with geophysics.

Data expected

The particular geology anticipated at a site should inform the selection of the geophysical method, so that the data will show some variation between the aquifer and aquitard. Whether the data are a record of electrode spacing and resistivity in a direct current resistivity survey or a series of wave traces from a ground penetrating radar survey, there must exist a contrast in material properties between the aquifer and aquitard for the geophysics to prove useful. In general, different lithologies have different material properties. For example, shale has a lower density and resistivity than limestone. Knowledge of the basic geology of the site helps identify potential variations in material properties.

Relevant hydrogeologic setting

A geophysical survey must be designed so that the contrast between the aquifer and aquitard will be evident. The method must also be appropriate to the setting. For instance, the signal from ground penetrating radar would be completely attenuated where an aquitard at a depth of 300 feet is saturated and covered by glacial till. In this setting, time domain electromagnetics would provide an image of the aquitard but with less resolution than ground penetrating radar.

Limitations

The limitations and caveats for geophysical investigations of aquitards are many. A fundamental limitation of geophysics is that it is an indirect measurement, most often of a physical property that is only a proxy for the property of interest. For example, we are interested in the K of a material, not the electrical resistivity, but we can measure the electrical resistivity more easily. Surface and borehole geophysical surveys are also notoriously non-unique, that is, many different earth structures yield similar data. It may not be possible to differentiate between an aquitard buried at 200 feet, 40 feet thick with a resistivity of 40 ohm-meters and an aquitard buried at 150 feet, 80 feet thick with a resistivity of 60 ohm-meters. Surface geophysical surveys can be affected by other factors such as topography and weather. Cultural features (e.g. radio towers, highways, power lines) may interfere with data collection at locations of interest.

Cost

Costs for geophysical surveys are often much less than for drilling but will vary greatly for the various methods and applications. A regional study of a deep bedrock aquitard using airborne electromagnetics will be much more expensive (several tens of thousands of dollars) than a ground penetrating radar (GPR) study of a shallow aquitard of several hundred square feet (several thousand dollars). Expertise and equipment to conduct geophysical surveys are available from many environmental engineering and water supply consultants.

Companion tools

Surface geophysical surveys should be designed and conducted after considering available data. Existing geologic and borehole geophysical logs are essential tools for designing a successful surface geophysical survey. A survey that is combined with these other data will identify the extent, depth and thickness of an aquitard in a way that would otherwise not be possible.

Table 3.1 Selected surface geophysical methods for investigation of aquitards.

Method	Property Measured	Information expected	Survey requirements/comments
Time domain electromagnetics	Electrical resistivity	• Extent • Depth • Thickness	• Aquitard thickness/depth should be greater than 5%. • Difficulties imaging multiple conductors
Frequency domain electromagnetics	Electrical resistivity	• Extent • Some depth information using different frequencies	• Shallow aquitards only (<30 feet deep) • Large areas mapped by airplane or walking.
Direct current resistivity	Electrical resistivity	• Extent • Depth • Thickness	• Can create a 2-D cross-section image of subsurface. • Sensitivity to near surface variations in resistivity may give erroneous results
Ground penetrating radar	Dielectric constant	• Extent • Depth	• Shallow aquitards only (<30 feet deep) • May not work below the water table • Rapid acquisition. • Good depth resolution
Seismic reflection	Seismic velocity	• Extent • Depth • Thickness	• Longer set-up time • Better depth and thickness resolution than other methods
Seismic refraction	Seismic velocity	• Extent • Depth • Possibly thickness if the underlying layer has a faster velocity than the aquitard	• Aquitard velocity must be greater than velocity of overlying materials or aquitard will not be evident • Good depth resolution

TIME DOMAIN ELECTROMAGNETICS, AN EXAMPLE OF SURFACE GEOPHYSICS

Operating Principle

Time domain electromagnetics (TEM) induces electric currents in the subsurface by passing current through a large transmitter coil positioned on the ground surface. The induced currents move downward and outward from the coil, producing a magnetic field. A small receiver coil in the center of the larger coil records the magnetic field as a function of time (Figure 3.4). The induced currents will persist longer in a conductive lithology than in a resistive lithology, as shown in Figure 3.5. The record of the magnetic field as a function of time can be used to derive a model of subsurface layers with various resistivities (Figure 3.6). More conductive layers generally correspond to clay and shale, so TEM surveys are well-suited to aquitard mapping.

Advantages

Acquisition of the data is relatively rapid; five to ten surveys can be conducted in a day, imaging depths up to 1000 feet. Much less area is required to conduct a TEM survey then is required for an equivalent direct current resistivity (DC) survey. A TEM survey to image to a depth of 600 feet need only be 300 feet on a side, while a DC resistivity survey to a similar depth requires about 2000 feet. TEM is scalable, the coil size can be varied to image shallow or deep targets.

Data expected

The data collected are a record of the magnetic field from the induced currents as a function of time (Figure 3.6). The data is fit to a layered resistivity model, and the model is subsequently related to the lithologies expected at the site.

Limitations

As is often the case with geophysical methods, the results are non-unique. The layered model shown in Figure 3.6 provides a good fit to the data, but similar models will give equally good fits. Table 3.2 compares two resistivity models. If several conductive layers are present, it is very difficult to arrive at a unique model. It is nearly impossible to separate the overlapping effects of multiple conductors and uniquely determine the resistivity, depth, and thickness of each conductor. Furthermore, even if the resistivity model is correct, the investigator must make assumptions about the relationship between resistivity and lithology, and extend these assumptions to K, the parameter that is usually of interest. We generally assume low electrical conductivity corresponds to clay mineralogy, which in turn corresponds to low K.

Cost

Rental of a TEM system to image depths of 200-300 feet is about $2000 per week. Expertise and equipment to conduct TEM surveys are available from many environmental engineering and water supply consultants.

Companion Tools

Surface geophysics should be used in conjunction with other information. The value of TEM surveys is greatly increased if the resistivities of the geologic formations are known (these may be obtained from a borehole geophysical log of normal resistivity). Similarly, a shallow DC resistivity log can be used to constrain the shallow portion of the resistivity model.

Site-specific example

TEM survey results and existing geologic logs were used to prepare a cross section showing the extent, thickness and depth of the shale facies of the Eau Claire Formation (Figure 3.7) in south-central Wisconsin. The TEM survey confirmed that the shale aquitard deepens and thickens near Arena, Wis. The survey provided a more accurate location of the edge of the shale then was obtainable with only geologic logs.

Table 3.2. Comparison of resistivity models for TEM sounding.

	Model 1	Model 2
Depth to shale (feet)	180	200
Thickness of shale (feet)	74	29
Resistivity of shale (ohm meters)	45	30
Model Fit (root mean squared error)	0.107	0.108

CORRELATION OF BOREHOLE GEOPHYSICAL LOGS

Relevant hydrogeologic setting

This method may be useful in any hydrogeologic setting where units of interest have contrasting geophysical properties to units above and below. However, certain geophysical records cannot be collected through cased boreholes, and some well construction materials may interfere with, or alter, the geophysical signal. Borehole geophysics may prove most useful in lithified settings, where uncased boreholes are commonly available and where installing large numbers of deep boreholes is prohibitively expensive. The use of borehole geophysics is not as common in unlithified settings because of the difficulty in maintaining an open hole, however the Indiana Geological Survey has demonstrated the utility of natural gamma logging (Chapter 5) to map glacial deposits (Bleur 2004).

Operating principle

Various types of borehole geophysical logs are described in Chapter 5 of this report. The logs are useful in mapping regional hydrogeologic units where properties of rock or sediment measured in the geophysical log (such as natural gamma radiation) serve as markers for the hydrogeologic unit of interest. Logs from wells across the region are correlated, accounting for changes in elevation due to topography and/or stratigraphic dip of the rock layers. Regional variations in the thickness and lithology of the hydrogeologic unit can be identified by comparing the logs.

Advantages

Geophysical logs provide a quantitative measure of the material properties and in some cases are therefore more objective than descriptions from some geologic logs. Geophysical logs supplement information from lithologic logs, providing more detail and accuracy about aquitard depth and thickness than can be obtained from drill cuttings. While high quality continuous core offers possibilities for quantitative geologic description, the cost of obtaining core may be prohibitively expensive. Geophysical surveys may be a cost effective method to supplement information from available cores.

Data expected

Measurements to support or refute a conceptual model of the regional extent and properties of an aquitard

Limitations

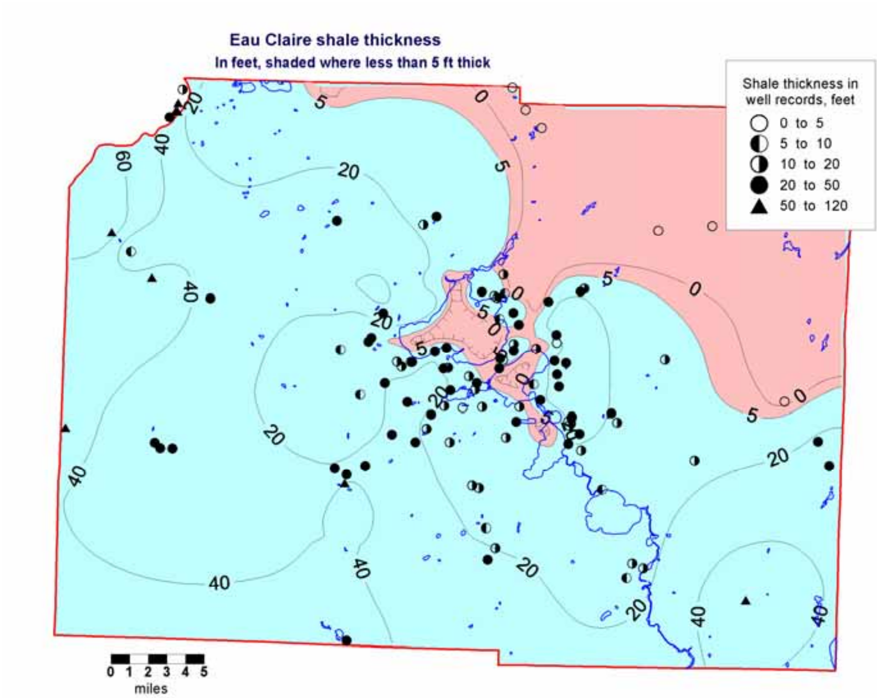
The method is only useful where a sufficient number of borehole geophysical logs have been collected across a region. Geophysical logs pertain to the geologic aspects of an aquitard, which do not necessarily represent the most important hydrogeologic features of an aquitard.

Cost

The cost of assembling the data is relatively minimal. If geophysical logs are not available, the cost of renting equipment and/or an experienced operator is on the order of several thousands of dollars per borehole.

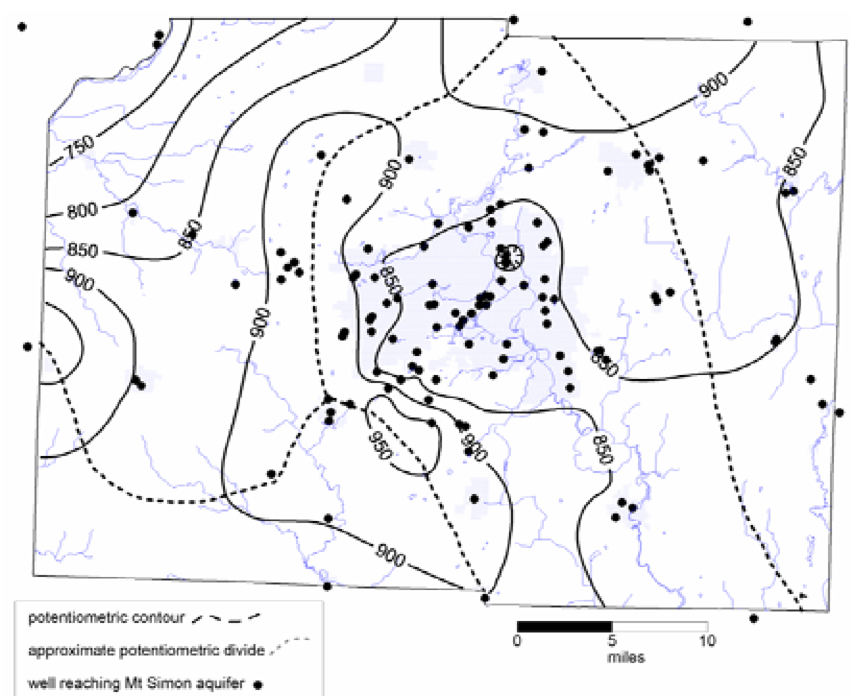
Site-specific examples

Logs of natural gamma in four wells in Dane County, Wis. are shown in Figure 3.8. The signature of the shale facies of the Eau Claire Formation can be seen in the increase in gamma at depths of 350 to 375 feet in well DN1371. The gamma logs show thickness decreasing from about 25 feet at DN1371 to less than 10 feet across the region. The decrease in the strength of the response indicates a change in lithology, suggesting a lower clay content in the interval from west to east.



Source: Adapted from Bradbury et al. 1999.

Figure 3.1 Map of the thickness of the shale facies of the Eau Claire Formation in Dane County, Wis.



Source: Bradbury et al. 1999.

Figure 3.2 Potentiometric surface map of the Mt. Simon aquifer in Dane County, Wis. Groundwater divides are shown as dashed lines.

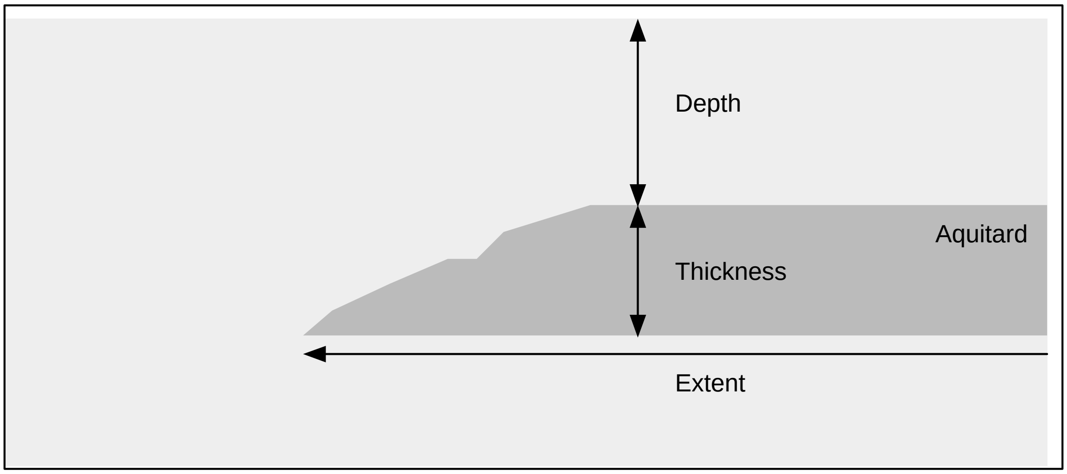


Figure 3.3 Aquitard information determined by geophysics.

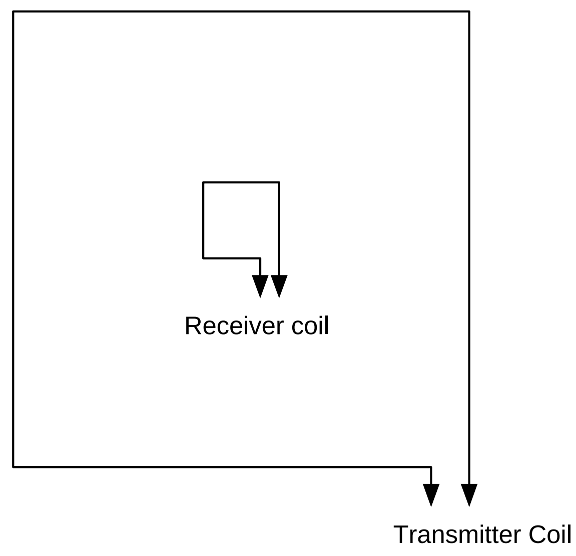


Figure 3.4 TEM sounding array. The penetration depth is usually 2-3 times the length of a side of the transmitter coil.

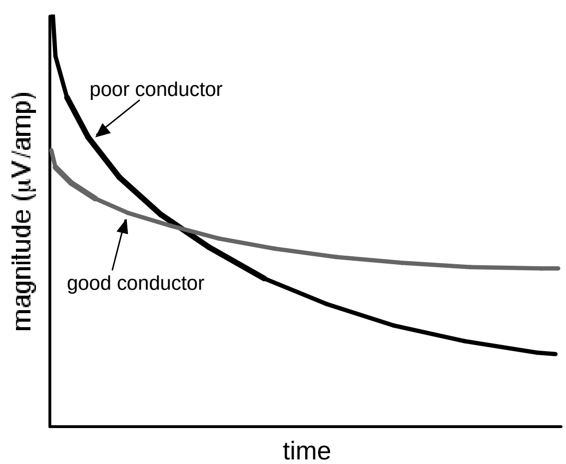


Figure 3.5 The magnetic field measured in the receiver coil. This will persist longer if a good conductor is present, shorter if a poor conductor is present.

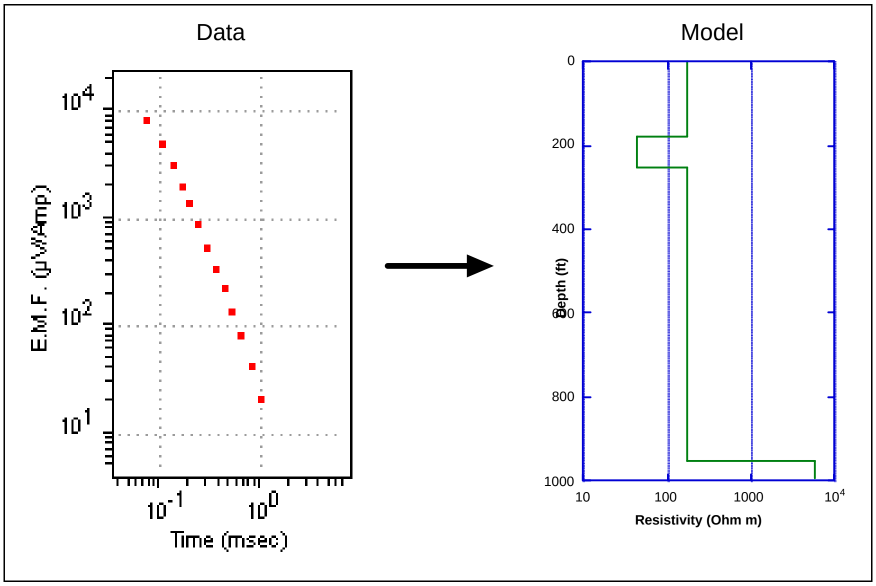


Figure 3.6 The record of the magnetic field in the center coil with time. This is used to derive a layered model of electrical resistivity with depth. Here, the Eau Claire shale is present at a depth of approximately 200 feet.

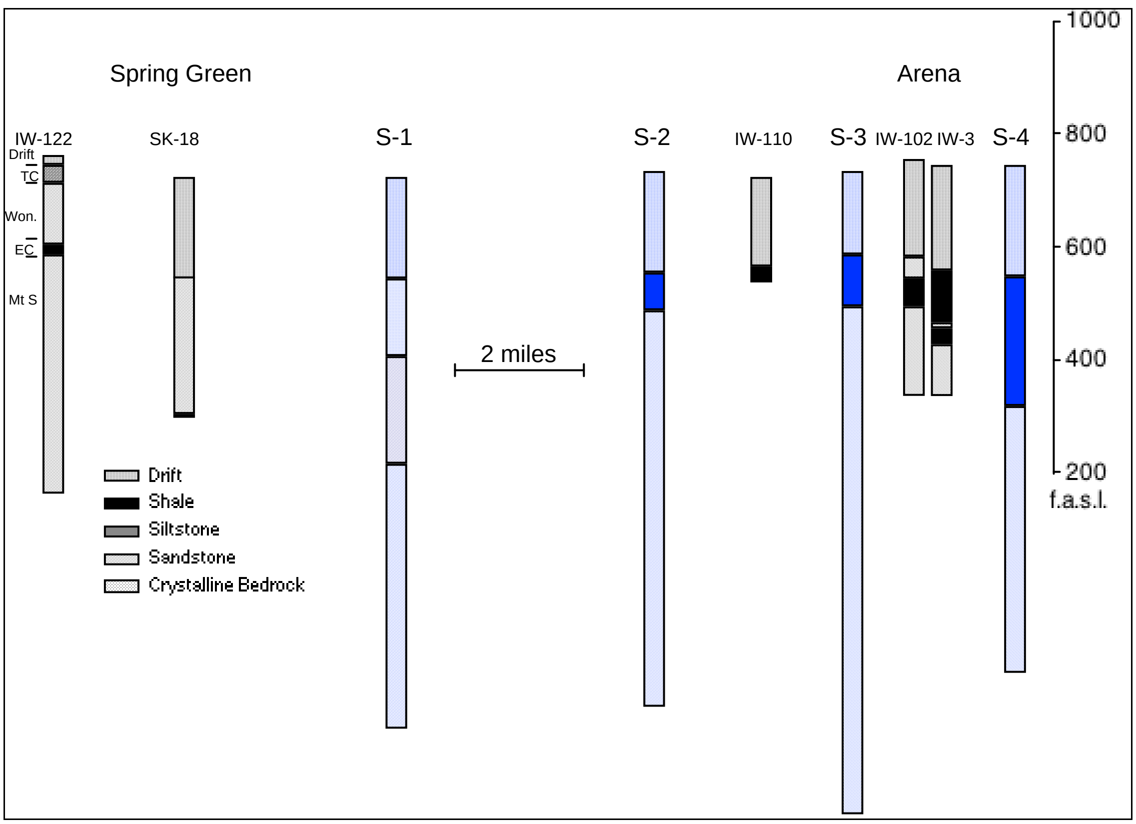


Figure 3.7 Cross section produced by geologic and TEM logs (S1-S4) across the Wisconsin River valley. Near Spring Green and Arena, Wis., the TEM survey shows that the edge of the Eau Claire shale is located between S-1 and S-2. The survey confirmed that the shale thickens and deepens between S-2 and S-4.

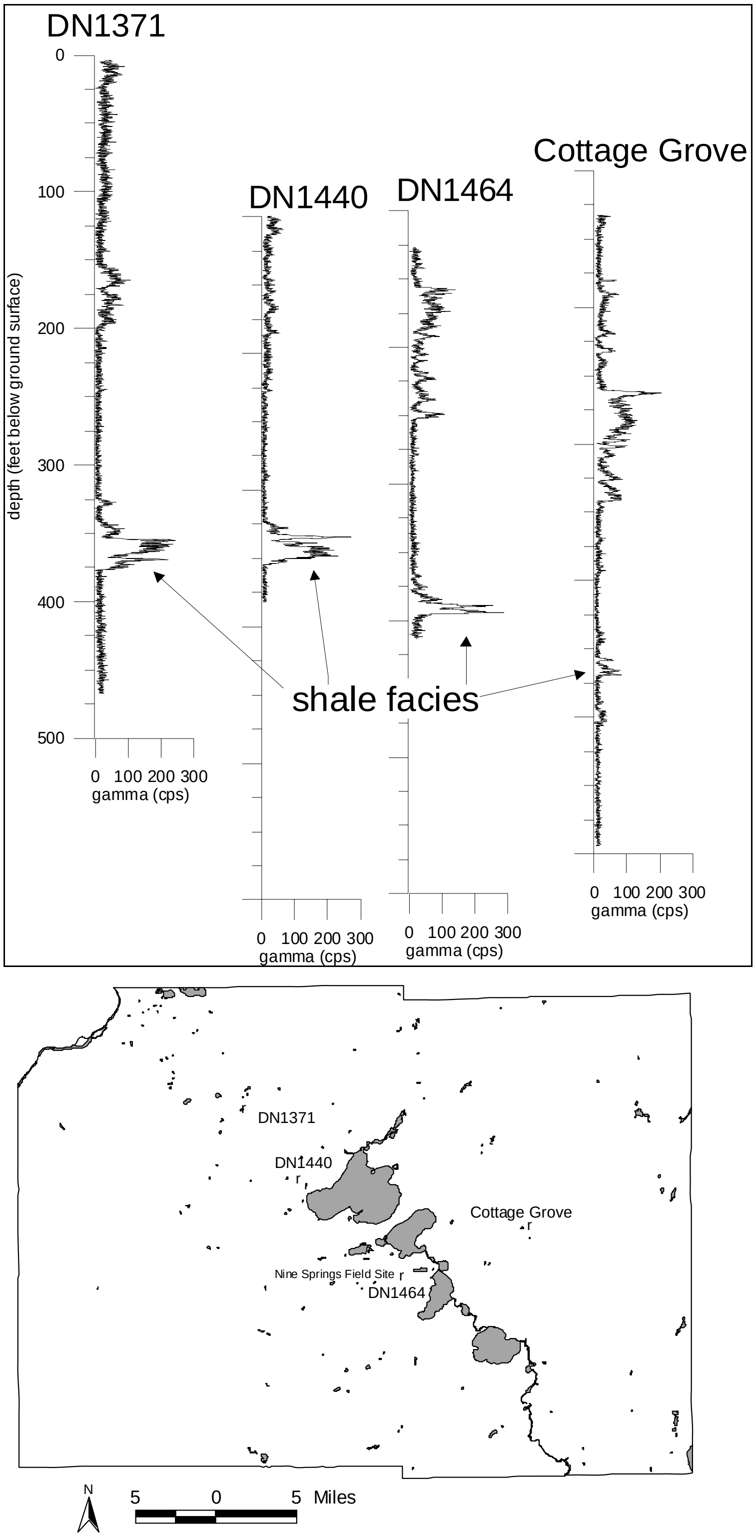


Figure 3.8 Gamma logs from four wells in Dane County, Wisconsin. Gamma is recorded in units of counts per second (cps). The logs are adjusted on the graph to account for differences in land surface elevation. Locations of wells are shown on the inset map.

CHAPTER 4
DRILLING METHODS IN AQUITARD STUDIES

Most aquitard studies are targeted at an individual well, well field, or contamination investigation. These investigations usually require detailed physical information about the aquitard at a specific site. The most common, and often only, techniques available to collect site-specific data from aquitards involve the installation and testing of borings and the subsequent instrumentation of the boring for data collection. While many drilling methods are available for hydrogeologic investigations, some are better suited to providing insight into the presence of, and protection offered by, aquitards. This chapter focuses on the subsurface drilling techniques most appropriate for aquitard investigations.

The drilling methods/equipment used for drilling in unlithified geologic materials is generally not the same as those used for rock drilling, although some drilling rigs can function well in both settings. Here we provide descriptions of six methods: two that are used only in unlithified media (hollow-stem augers and direct push coring), one used in lithified media (diamond-bit coring), and two used in both environments (rotosonic and rotary drilling). This list is not exhaustive; other drilling methods may offer cost-effective approaches to providing the information sought.

When the decision is made to drill at a particular location, there can be one or more objectives for the drilling:

1. Acquire sediment or rock samples (usually undisturbed core samples) for determining lithology, physical and/or chemical properties or in some cases for measurement of contaminant or environmental isotope concentrations
2. Provide a hole for conducting geophysical logging, hydrophysical logging, or other types of borehole measurements (e.g. hydraulic head, K_h, K_v), typically in lithified settings
3. Provide a hole for installation of groundwater monitoring devices, such as a monitoring well, multilevel system or buried pressure transducers

In some cases, particularly in lithified deposits, the hole meets all three of the functions outlined above. Decisions as to whether or not the drilling must provide core samples and whether or not the cores must be continuous and relatively undisturbed is important because this narrows the choice of drilling methods and affects the cost of drilling. In some aquitard assessments, there is critical need to directly observe and conduct various types of measurements on core samples. These activities provide information about preferential pathways (e.g. fractures) and/or the presence or absence of chemical or isotopic evidence of such pathways. For example, core samples of unlithified aquitards can be used for extraction of pore water by squeezing or centrifuging and rock core samples may yield pore water by centrifuging or other means.

In unlithified aquitards, objective number (2) above is rarely pursued; information on the geologic and hydraulic characteristics of the media is obtained by other means (e.g. core inspection, testing after the monitoring system is installed). In lithified media, the open borehole is valuable in its own right because it provides access for geophysical logging and other types of borehole measurements that provide insights generally unobtainable by other means.

Once the decision is taken to drill a hole, further decisions are required for the hole to meet specific technical/scientific data needs. For example, if one of the objectives of the drilling is to create a hole for installation of a depth-discrete multilevel monitoring system, the particular type of multilevel system selected may dictate the minimum or maximum borehole diameter. If the investigation requires assessment of the presence/absence of vertical fractures through an aquitard, drilling one or more angled boreholes (often referred to as "directional drilling") is useful.

During any drilling operation, a geologist should be at the drill site to collect and describe the samples or core using a standardized and organized methodology. Field guides for the description of glacial materials and fractured rocks are available from many sources. Three useful references are *AGI Data Sheets* (Dietrich and Foose 1982), *Field guide for soil and stratigraphic analysis* (Midwest Geoscience Group 2001), and *Field guide for rock core logging and fracture analysis* (Midwest Geoscience Group 2004).

HOLLOW STEM AUGER DRILLING

Relevant Hydrogeologic Setting

Hollow stem auger (HSA) drilling is usually successful in surficial, unlithified deposits lacking boulders or large cobbles. HSAs can penetrate consolidated tills and most other shallow unlithified or poorly-lithified geologic materials to depths up to about 150 feet.

Operating Principle

In HSA drilling, downward pressure applied to a hollow, continuous flight auger turns the auger into the geologic medium. Drill cuttings are brought to the surface by the rotation of the auger. A drill rod with a bit is used in the center of the hollow stem auger to help remove cuttings from the center and advance the auger. Deposits of unconsolidated, saturated sand can flow up into the center of the auger stem (referred to as "heaving sands"), complicating or precluding sample collection and well installation. When heaving sands are encountered, a plate placed at the bottom of the lead auger may aid in preventing inflow of the sand into the hollow stem. Water may be poured or pumped into the hollow stem to reduce the pressure differential and reduce the heaving. However, adding water may create concern about the integrity of groundwater samples collected after drilling is completed. Samples of geologic material can be collected by driving a split-spoon sampler through the hollow auger stem. Specialized coring devices, piston cores, are available that minimize sample disturbance. These can be helpful to search for evidence of preferential pathways such as fractures. A monitoring well or multilevel system can be installed in the hollow stem, while the augers hold the boring open, preventing collapse of the surrounding formation.

Advantages

HSA has the advantage of a wide base of experience; it is well-known and understood by drill rig operators and regulators. HSA drilling and core sampling are readily available from contractors across North America. These drill rigs are generally available to accommodate on-road or off-road conditions in difficult terrain, as well as drilling inside buildings. HSA drilling is relatively quick, and an experienced crew can install several shallow wells in a day. Little or no fluid is used during the drilling, reducing the amount of effluent that must be disposed of and reducing the chance of diluting formation water with drilling fluid.

The diameter of HSAs are sufficiently large (up to 10.25 inches) to allow installation of a monitoring well with proper seals and sand pack. Many state monitoring well codes may require that a seal be installed to prevent vertical migration of contaminants; this requirement may limit applicability of other drilling methods.

Limitations

HSA drilling is not feasible in lithified media or in unlithified media containing boulders or hard layers. HSA is generally limited to depths under 150 feet in favorable conditions, and at many sites the maximum depths may be much less. Cuttings collected from the auger may not be representative of the formation. A core sampler, e.g. split spoon, should be used if a representative sample is required. However, split spoon methods will cause some deformation and smearing during collection. Deformation may be minimized by use of piston samplers.

Cost

HSA drilling services cost about $15 per foot plus mobilization.

DIRECT PUSH DRILLING

Relevant Hydrogeologic Setting

Direct push (DP) drilling can be done in surficial unlithified deposits lacking boulders or hard or very dense layers. DP drilling has best prospects in minimally consolidated surficial deposits such as lacustrine deposits, backswamp deposits and some types of fluvial deposits. DP drilling can penetrate depths up to 150 ft below surface in favorable conditions.

Operating Principle

In direct push drilling, the drill casing or rods with soil sampler attached is driven down into the subsurface using force applied to the top of the casing or rods. The purpose of this drilling is to take cores of the geologic medium or to drive a piezometer or monitoring well to the desired monitoring zone. The piezometer can be a pressure transducer or a standpipe type piezometer. DP drilling differs greatly from rotary drilling or auger drilling because it involves no rotation of the drill casing or rods. DP drilling differs from rotosonic and sonic drilling in that the casing or rods are pushed by constant force or impact force. If impact force is used, the frequency is much less than that of rotosonic or sonic drilling. DP drilling in North America is most commonly done using rigs manufactured by GeoProbe Inc.

Advantages

DP drilling is readily available from contractors in nearly all parts of North America. DP rigs are available to accommodate on- and off-road conditions in difficult terrain and drilling inside buildings. DP drilling does not bring cuttings or any other subsurface material to surface. Therefore, piezometers or monitoring wells can be installed in contaminated media without generating contaminated cuttings for disposal. In geologic media in which DP drilling is feasible, it may be the lowest cost method of drilling suitable for coring and piezometer or monitoring well installations.

Limitations

DP drilling is not feasible in rock or in unlithified media containing boulders or hard layers. DP drilling generally is not feasible to depths greater than 150 ft, and at many sites maximum depths are much less. DP rigs cannot drive casings with diameters greater than 3 or 4 inches, which limits their capability for installation of commercially available multilevel monitoring systems with reliable sand packs and seals. In contrast, rotosonic drilling typically uses 5- to 7-inch casing well suited to installation of multilevel systems.

Cost

DP drilling services are typically available at rates between $1000-$2000 per day. Some cases the drilling can be obtained on a per foot or per well basis. The rates vary depending primarily on the size of rig needed.

ROCK CORING

Relevant hydrogeologic setting

Rock coring techniques are well-suited to lithified formations. Casing must be installed through any unlithified overburden. The rock drilling proceeds inside the casing to greater depths.

Operating principle

Solid core samples are collected by advancing a diamond bit on rotating drill rod. The rock is collected in a core barrel mounted directly behind the bit. The core barrel may be retrieved from the hole on a wire line. Water, in some cases mixed with air, is typically used as a drilling fluid. In weakly lithified rock, a drilling additive or mud is mixed with the water to increase core recovery.

Advantages

Good sample integrity in bedrock formations; core may be suitable for lab analyses of permeability, porosity and contaminants.

Data expected

Rock coring drilling methods return continuous samples of the formations drilled through. Core shows lithology, stratigraphy, and small-scale features such as fractures. The core may be analyzed in a laboratory for physical characteristics such as porosity, K, or organic carbon content.

Limitations

May have poor recovery in weakly lithified sandstones or difficulty advancing the core barrel in highly fractured bedrock. Care must be taken to differentiate between natural fractures and those caused by drilling. Such differentiation is typically not possible for some core breaks.

Cost

Drilling contractor costs range from $10 to over $100 per foot depending on depth, diameter, and drilling conditions. Additional costs are incurred for geologic supervision and core description.

Companion tools

Borehole visualization, geophysical logging, and hydraulic testing of the borehole (described in Chapters 5 and 6) yield further insight into aquitard properties.

Site-specific examples

Rock core was recovered from well NS-3 at the Nine Springs from a depth of 272 to 308 feet. Prior to rock coring, the mud rotary drilling method was used to install casing from the ground surface to 272 feet. The core showed that at this location, the shale facies of the Eau Claire Formation is 7.5 feet thick, from a depth of 288 to 295.5 feet below ground surface. Although the shale facies is easily recognized in the core, it is difficult to determine which fractures seen in the core are present in the aquitard and which fractures were caused by the rock coring technique (Figure 4.1).

ROTOSONIC DRILLING

Relevant hydrogeologic setting

Rotasonic drilling is particularly effective for collecting relatively undisturbed, continuous samples of unlithified sediments. Drilling in bedrock formations may also be successful, although recovery may be poor for very hard rock types.

Operating principle

Two drill pipes are advanced by rotary and vibrating power; no drilling fluids are used. The bit is on the end of the inner pipe, which serves as the core barrel and is advanced ahead of the outer pipe. The outer pipe prevents the hole from collapsing while the inner pipe is retrieved from the hole and the core sample is extruded (Figure 4.1). The outer pipe also prevents formation collapse during well construction.

Advantages

Large-diameter core (from 3 to up to 9 inches) preserves small sedimentary features, such as fractures and thin seams of interbedded sand (Figure 4.1); relatively rapid drilling times for high quality samples; well-suited to unlithified deposits; depths over 400 feet in ideal conditions; does not introduce drilling fluid (mud, air or water) to formation or core. Core may be suitable for lab analyses of permeability, porosity and contaminants.

Data expected

Continuous, relatively undisturbed core of overburden or bedrock for accurate descriptions of lithology and stratigraphy, and for physical testing.

Limitations

Cost of mobilization may be high because there are relatively few rotosonic drilling rigs. Core recovery may be poor in very hard formations.

Companion tools

In lithified materials, a rotosonic-cored hole provides access to the subsurface for visualization, geophysical logging and testing techniques (Chapters 5 and 6). In unlithified deposits, temporary casing (such as inexpensive plastic pipe) can be used to prevent collapse of the hole after the drill pipe is removed.

Cost

Rotasonic drilling charges are on the order of $45 to $55 per foot. Mobilization distance also affects cost.

ROTARY DRILLING

Relevant hydrogeologic setting

Rotary drilling techniques are well-suited to consolidated rock. Casing must be installed through any unconsolidated materials that overlie the formations of interest. A down hole, percussion hammer may be used where the rock is particularly hard. Rotary drilling is sometimes valuable in unlithified settings (using mud to keep the hole open) in order to collect geophysical logs in an uncased hole or to collect undisturbed samples of unlithified materials with a Shelby tube sampler.

Operating principle

Rotary drilling methods utilize a rotating bit to drill though geologic materials. Water, drilling mud, or compressed air is used to cool and lubricate the drilling system and to circulate the cuttings through the drill stem, up to the ground surface. Using air as a drilling fluid provides the cleanest set of cuttings, whereas mud introduces particulate matter. Push-type tube samplers can be collected during rotary drilling in unlithified aquitards.

Advantages

Rotary drilling is readily available, and relatively fast and inexpensive (when not collecting continuous core). When samples of drill cuttings are collected carefully and at short, regular intervals, this drilling method provides information regarding the depth, thickness, and general lithologic characteristics of stratigraphic layers. Rotary drilling can be used to depths on the order of hundreds to thousands of feet.

Data expected

Rotary drilling methods return cuttings (chips or fragments) of the formations drilled through. Cuttings can be collected continuously or at regular intervals. Samples should be examined and described by a geologist. Core samples can be collected from rotary drilled holes in unlithified aquitards using push-type tube samplers.

Limitations

The method significantly disturbs the samples, typically returning rock chips where the rock is well cemented or lithified, and returning a mix of grain sizes where the rock is poorly lithified. Rotary drilling does not preserve any geologic structure in the samples, such as bedding, laminations, or evidence of fractures. Because fine-grained sediments may travel at a different velocity than coarse cuttings, the cuttings may be mixed to an unknown degree as they circulate up through the drill stem to the ground surface. The samples are mixed with the drilling fluid used and may not be suitable for contaminant analyses.

Cost

Approximately $10 per foot of drilling, $10 per foot of casing, plus the cost of grout and mobilization. At the Nine Springs field site (see Appendix A), well NS-1 was cased to 44 feet below surface and drilled to a depth of 310 feet for a total cost of $4800.

Companion tools

After drilling a hole in rock, geophysical and visualization logs can be collected in the borehole to supplement information from the cuttings. The geologic and geophysical logs provide the basis for design of borehole hydraulic testing and an appropriate monitoring system.

Site-specific examples

The geologic log of well NS-1 (Appendix A, Figure A.4) at the Nine Springs field site was generated from cuttings collected using air rotary drilling. The cuttings indicate that at this location, the Eau Claire aquitard consists of interbedded shale, sandstone and dolomite at a depth of about 275 to 294 feet below ground surface. Observations made during drilling indicated that about five feet of sandstone underlying the shale was exceptionally hard. The drilling and cuttings yielded no insight into the extent of fractures in any of the geologic formations.

Figure 4.1 Core from two drilling methods. Top: drillers extrude rotasonic core into plastic sleeve. Middle: rotasonic core collected from 320 ft depth in glacial deposits preserves heterogeneity in clayey material. Bottom: Diamond-bit rock core method used to core Eau Claire shale from the Nine Springs research site. Fracture 1 may be natural, fractures 2 and 3 were likely caused by drilling.

CHAPTER 5
OBSERVATIONS OF BOREHOLES AND CORE

After drilling is completed, the borehole provides access to the subsurface for downhole geophysical and visualization tools, and depending on the drilling method, core may be available for physical testing and analyses. Observations of the subsurface made through borehole geophysical or image logging involve lowering a series of small-diameter probes ("tools") through a borehole (or an existing well where the pump has been removed). The tools transmit various signals via cable to a processor and computer at the well-head. The information is usually processed in some fashion to determine properties of the geologic formations.

If rotosonic or diamond-bit coring methods are used to install boreholes, the recovered core provides continuous, high-quality samples of the aquitard. These may be examined for structural features and tested for their physical properties.

This chapter catalogs these methods, starting with a section on temporarily sealing boreholes to prevent inadvertent contaminant migration through a borehole left open for the purposes of aquitard investigation. Geophysical logging and imaging are described, as are methods for testing core.

TEMPORARY SEALING OF BOREHOLES IN LITHIFIED ENVIRONMENTS

This method is mainly relevant to lithified geologic media because open drill holes or long open well bores in these media typically have *hydraulic cross connection* (i.e. Figure 2.2). Holes left open in unlithified deposits are much less common and even when such holes are left open, some degree of caving or sloughing usually occurs, which prevents use of this method.

Operating Principle

The goal of this method is to prevent flow from occurring in open drill holes or well bores because such flow can cause disturbance to the chemistry of the formation water, thereby causing future sampling of wells or multilevel systems installed in these holes to provide unrepresentative data. Cross connection effects are particularly strong in sedimentary rock. Cross connection effects occur because head differentials between various formations encountered in an open borehole may cause flow into the hole from one fracture or zone to a fracture or zone at some other elevation.

This method involves insertion of a continuous but temporary packer into the hole to provide a seal throughout the hole down to the bottom or near the bottom. The temporary seal should be used when a borehole installed at a contaminated site is not being used for logging or testing purposes, in the period before a monitoring well or multilevel system is installed in the borehole. Continuous packer type temporary seals are available from two commercial suppliers. Solinst Canada provides a continuous rubber packer in 10 foot or longer segments that are coupled to create the desired length (www.solinst.com). Another type of continuous packer is available from Flexible Liner Underground Technologies Limited (www.flut.com). This system consists of a continuous length of urethane-coated nylon tubing installed down the hole using water pressure.

The continuous packers described here seal the entire hole, whereas standard packers seal only a short segment of the hole. More than one standard packer can be used, however many more may be necessary to substantially prevent cross connection in an open hole. A string of conventional packers may be excessively expensive compared to a continuous packer.

Limitations

The use of temporary continuous packers to prevent borehole cross connection can be particularly time consuming if the continuous packer is inserted and then removed from the hole on numerous occasions. Thus, it can be desirable to schedule borehole geophysics, borehole flow metering and packer testing to minimize the number of insertions and removals.

Cost

Borehole liners and continuous packers cost on the order of $10 to $20 per foot.

Examples

Sterling et al. (2005) provide an example of long term cross-connection effects caused by an open drill hole in contaminated sandstone.

BOREHOLE VISUALIZATION TECHNIQUES

Operating principle

Borehole visualization refers to the collection of optical or acoustic images of the inside surface of a well or rock borehole using a sensor suspended on a cable from the surface. Such information helps understand and interpret the geologic features exposed in boreholes, such as different rock units, sedimentary features, fractures, and dissolution features. There are currently three categories of visualization tools in common use. The simplest of these, *borehole television,* obtains a black-and-white or color image of the borehole and records the analog image on video tape. These images are then displayed on a television monitor. More sophisticated tools include the *digital optical televiewer* and the *digital acoustic televiewer*. Both these digital tools provide detailed images that are oriented to dip and direction inside the borehole. The optical televiewer collects a high-resolution optical image using a digital camera, while the acoustic televiewer collects waveform data resulting from the reflection of acoustic signals from the borehole walls. Data from both these digital tools can be precisely plotted versus depth in the borehole and enhanced using various software packages.

Advantages

Borehole visualization provides more direct and easily understood information about the subsurface than interpretations from well cuttings or other geophysical logs. If physical sampling of core is not required, visualization can save money by substituting a virtual (visual) core for core drilling. Borehole television is especially useful for viewing large features encountered in boreholes, such as voids, fractures or irregularities in the casing. Motion can be discerned on television logs, showing the flow of groundwater into the borehole from fractures located above the water table or sediment movement in the water column. The digital televiewers allow optical or acoustic data to be plotted precisely in relation to depth and other geophysical logs, and because the tool is oriented the data can be used to determine the orientation of the borehole and of fractures in the borehole wall.

Data expected

Borehole television produces a standard television view using either a fish-eye lens (downhole) or side-hole view. Digital televiewers produce a wealth of digital optical or acoustic information and require specialized software for processing and visualization. The digital data allows the construction of "virtual" core images.

Relevant hydrogeologic setting

These tools are useful in open, uncased portions of boreholes or wells, which are typically available in lithified formations. The acoustic televiewer can sometimes "see" through plastic well casing. In unlithified settings, drilling tends to smear sediment along the borehole wall so that even if the uncased borehole remains open, fractures and other small-scale features may be obscured.

Limitations

Optical tools can be run in air or in clear water; they work poorly in turbid water. Acoustic tools require fluid-filled boreholes but can work well in turbid water. Acoustic and optical tools require specialized equipment and may not be locally available. They generally require slow logging speeds (2-3 ft/minute). Use of these methods is typically restricted in unlithified settings.

Cost

Borehole television systems and services are widely available. Costs vary but are on the order of several hundred to $1000 per well televised. Digital optical and acoustic tools and services are available from a limited number of sources and consequently are more expensive – in the range of several $1000 per hole for equipment, operator and data analysis.

Companion tools

Borehole imaging should usually be accompanied by other borehole data such as standard geophysical logs, sample descriptions, and stratigraphic interpretations.

Site-specific examples

The US Geological Survey gives a number of examples of borehole visualization at http://ny.water.usgs.gov/projects/bgag/factsheet.text.html. Figure 5.1 compares the three visualization techniques at sites near Madison, Wis.

NATURAL GAMMA LOGGING

Relevant hydrogeologic setting

Natural gamma logs are useful in unlithified and lithified materials to determine the depth and thickness of clay and shale beds. Gamma logs may be collected in cased and open boreholes.

Operating principle

Natural gamma radiation is emitted from radioactive isotopes of potassium, uranium, and thorium. These isotopes are commonly found in the clay minerals of clay and shale beds that make aquitards. They are found less often in the quartz sands and carbonates that commonly constitute aquifers. For this reason, natural gamma radiation can be a good indicator of the presence of an aquitard in a sedimentary sequence.

A gamma log is collected by lowering a downhole probe through a borehole. A computer at the groundwater surface records the measurements (gamma counts per second with depth) transmitted through the cable attached to the probe. A higher count of gamma radiation usually means that more clay is present, a lower count means that the formation is “cleaner”, that less clay is present.

Advantages

Although the lithology of entire formations may be described as a single material in drilling logs, only a portion of the formation may function as an aquitard. Natural gamma logs are useful to quickly identify parts of the formation that are likely clay-rich. These logs are easily collected and interpreted. Data is collected quickly, at logging speeds on the order of ten feet per minute. Gamma logs can be collected simultaneously with other geophysical logs (e.g. natural resistivity and self-potential) and gamma can be recorded through steel and plastic well casing.

Data expected

A natural gamma log is a record of the counts of natural gamma radiation detected per second with depth. In addition to recording higher concentrations of clays, the counts per second will vary with the borehole diameter, grouting, and casing material and thickness. The natural gamma log should be coupled with a geologic log to provide general lithology and stratigraphy. The natural gamma log can complement the geologic log by giving information at a higher resolution.

Limitations

Natural gamma logs respond to potassium, uranium, and thorium. Granites, glauconitic sandstones, basalts and many other lithologies may contain these elements and yield a high gamma count. Although these rock types often function as aquitards within a groundwater system, in the absence of other information (such as a geologic log) a high natural gamma count cannot immediately be interpreted as clay or shale.

Large boreholes (greater than about 30 inches in diameter) with thick casings, such as some high capacity water wells, may also impose limitations on natural gamma logging. Large diameter boreholes will cause low and smeared gamma counts, dampening the gamma emitted by clay and shale beds. A small diameter borehole will result in higher counts per second that a large diameter borehole in the same formation, because the probe is closer the formation in the smaller borehole.

Grout often contains potassium, and grouted wells can cause higher gamma counts. Steel casing will block some of the gamma rays, resulting in a lower gamma count. A gamma probe's radius of detection is about six inches. Gamma rays emitted from a thin, highly concentrated shale bed will be detected by the probe when it is above, alongside and below the bed. This results in a smearing of the signal and makes resolution of thin individual beds difficult.

Cost

Rental of the gamma probe is about $50 per day. Rental cost of the full suite of probes and the logging console, winch and cable is on the order of several thousand dollars. Expertise and equipment are available from environmental engineering and geophysics consulting firms.

Companion tools

Before collecting a natural gamma log, a geologic log and well construction report can be used to determine potential sources of natural gamma radiation in the stratigraphy. The natural gamma log can be used with a normal resistivity log to differentiate between clay and shale, and metamorphic and igneous rock. Clay, shale and metamorphic and igneous rock may have high gamma signatures, but clay and shale typically have low normal resistivity while the metamorphic and igneous rocks have high resistivity.

Site-specific examples

Figure 5.2 shows the natural gamma log for NS-1 at the Nine Springs field site. The peaks in the gamma log correlate to shale-rich intervals of the Eau Claire Formation and show significant contrast to the gamma signatures of the overlying and underlying sandstone aquifers. Figure 5.3 shows a regional gamma log correlation. The Maquoketa formation is composed of interbedded shale and dolomite, where the shale has higher gamma counts than dolomite. The two logs are remarkably similar, suggesting that there is relatively little variation in lithology between the two boreholes. Additional information on natural gamma borehole logging can be found at http://ny.water.usgs.gov/projects/bgag/intro.text.html and in Keys (1997). The Indiana Geological Survey makes extensive use of natural gamma logs in regions characterized by thick sequences of unlithified glacial deposits (Bleur 2004).

NORMAL RESISTIVITY LOGGING

Relevant hydrogeologic setting

Normal resistivity logs are typically collected in lithified environments. Although they may be useful in unlithified deposits, these logs cannot be collected through cased portions of wells.

Operating principle

Electrical resistivity logs measure how well a formation conducts electricity. A material that easily conducts electricity has a low resistivity while one that is a poor conductor of electricity has a high resistivity. The electrical resistivity of earth materials is controlled by the pore water and clay content of the material. Saturated rock or sediment with high porosity is a good conductor and will have a low resistivity. A saline pore water also causes low resistivity. Clays are good electrical conductors and rock and sediment with high clay mineral content are good conductors. These relationships make normal resistivity logging useful for the study of clay and shale aquitards. Clay and shale have high porosity and high clay mineral content, resulting in low electrical conductivity. The current is injected through the A-electrode and the resulting voltages are measured at the M8, M16, M32, and M64 electrodes. These electrodes correspond to spacings of 8, 16, 32, and 64 inches between the current and voltage electrodes (Figure 5.4). Longer spacings provide deeper penetration of the current into the formation with less influence from the borehole fluid, and shorter spacing give higher resolution. Additional information about normal resistivity logging is presented by Keys (1997) and on the US Geological Survey web site: http://ny.water.usgs.gov/projects/bgag/intro.text.html.

Advantages

Normal resistivity logs are easy to collect and interpret. They are low cost, and may be obtained simultaneously with natural gamma logs. The normal resistivity log differentiates between good and poor conductors of electricity, which may correlate to lithologies that form aquitards and those that form aquifers.

Data expected

The data collected are a record of resistivity with depth. Saturated shale and clay have resistivities less than 100 ohm-meters (ohm-m). Sandstone has resistivities on the order of 100-1000 ohm-m while; carbonates and crystalline rock have resistivities exceeding 1000 ohm-m.

Limitations

Normal resistivity logs cannot be collected through cased portions of wells or in the unsaturated zone. The probe must be submerged in water to allow electricity to flow through fluid in the borehole and into the formation. If the borehole diameter is large, on the order of 30 inches or more, most of the electricity flows into the borehole and not into the formation preventing an accurate measurement of the formation resistivity.

Normal resistivity logging may give ambiguous results. For example, it may be difficult to differentiate between shale with fresh pore water and sandstone with high-salinity pore water.

Cost

Rental of the normal resistivity tool is about $75 per day. Rental cost of the full suite of probes and the logging console, winch and cable is on the order of several thousand dollars. Purchase cost of the probes, console, winch and cable are on the order of $30,000 to $50,000.

Companion tools

The normal resistivity log is often used in conjunction with a natural gamma log to differentiate between clay and shale, and many crystalline rocks. Clay, shale, and many crystalline rocks will give high gamma ray counts, but clay and shale have low normal resistivity compared to that of igneous and metamorphic rocks.

Site-specific examples

Figure 5.5 shows the 8-inch electrode spacing of the normal resistivity log for NS-1 located at the Nine Springs field site. The shale facies can be seen at depths between 280 and 295 feet. The higher resistivity in the adjacent sandstones (above and below the shale, at depths of 208 and 310 feet) correspond to increased cementation in the sandstone. There is less porosity and less pore water available to conduct the electricity in well-cemented areas within the rock.

BOREHOLE CALIPER LOGGING

Relevant hydrogeologic setting

Borehole caliper logs are collected in boreholes open to bedrock formations

Operating principle

The caliper log provides a continuous measurement of borehole diameter. A downhole probe is lowered to the bottom of a borehole. The arms of the caliper expand or contract to the diameter of the borehole as the probe is pulled up through the borehole. Surface equipment records the measurements transmitted up to the ground surface through the cable attached to the probe. Changes in diameter of the borehole indicate the size and location of fractures or irregularities caused by drilling or lithology.

Advantages

The caliper log is a simple method for identifying locations of fractures that are on the order of 2 mm or greater. It may be redundant in cases where borehole visualization methods are applied.

Data expected

Continuous measurement of borehole diameter indicating the location and size of horizontal fractures.

Limitations

The caliper arm length must be appropriate for the diameter of the borehole in order to produce a useful log. Other tools must be used in conjunction with the caliper log to determine which fractures are water-producing. The caliper log may not detect vertical fractures intersected by the borehole, unless one of the caliper arms happens to align with the vertical fracture. Often the caliper tools are not sensitive enough to detect small but hydraulically important fractures.

Cost

Rental of caliper tool is about $50 per day. Rental cost of the full suite of probes and the logging console, winch and cable is on the order of several thousand dollars. Purchase cost of the probes, console, winch and cable are on the order of $30,000 to $50,000.

Companion tools

The caliper may be used in conjunction with the heat pulse flow meter or fluid temperature and fluid resistivity logs to determine if a specific fracture contributes flow to a borehole.

Site-specific examples

Figure A.4 (see Appendix A) shows a caliper log collected at well DN1440. Several fractures are apparent in both the Wonewoc Formation and the upper portion of the Eau Claire Formation. Additional information about the fractures is provided by the fluid resistivity and temperature logs discussed in Chapter 6.

X-RADIOGRAPHY FOR IDENTIFICATION OF STRUCTURE IN CORES

Relevant Hydrogeologic Setting

X-radiographs can be used to identify depositional and structural features in core samples of unlithified and lithified deposits, however, this method generally has value only for studies of unlithified aquitards.

Operating Principle

An x-ray photograph (referred to as an x-radiograph) is taken of a slab cut from the core sample, either across the core or along the length of the core. The slab, about 1 cm thick, is placed on a sheet of photographic paper and the x-ray beam is directed across the slab to cause activation of the photographic paper, which shows sedimentological and structural features in the core slab based on material density variations. X-radiographs are used to determine the presence of small-scale stratification (e.g. laminations or microbedding) and secondary structural features such as roots or root hole fractures, organism burrows, which may provide pathways for contaminant migration. X-radiographs have been used in studies of clayey aquitards in the Gulf Coast region of the United States where they have shown clearly the sedimentological nature and structural features of cores.

Advantages

X-radiography is the only method available that provides clear, detailed images of the internal structure of core samples. The capability for this method to identify and elucidate small scale features of core relevant to potential preferred pathways greatly exceeds that of visual inspection of cores and normal photography of cores.

Limitations

The cores should be collected carefully in a manner that minimizes physical disturbance of features internal to the core. Few laboratories are available to do the x-radiographs.

Availability

We are aware of two laboratories that do x-radiography on cores: Alberta Research Council (contact Steve Moran, email: moran@arc.ab.ca) and at Louisiana State University (contact Richard H. Kesel, Department of Geography and Anthropology, Louisiana State University, email: gakesel@lsu.edu).

Site-specific Examples

Examples of x-radiographs are provided by Potter, et al. (2005). Figure 5.6 shows an x-radiograph of a fractured clayey aquitard.

CORE-SCALE MEASUREMENTS OF PHYSICAL PROPERTIES

Relevant Hydrogeologic Settings

Several drilling methods provide the means to obtain cylindrical cores from lithified and unlithified aquitards. The cores can be used in the laboratory for measurements of physical properties. The appropriate coring methods for a particular aquitard are those providing cores that are only minimally disturbed, because the goal of laboratory measurements of physical properties is to obtain parameter values representative of the aquitard material under field conditions at the core scale.

Relevant Physical Properties

There are many physical properties that can be measured in the laboratory, however only a few are commonly important in investigations of aquitard integrity; these are: K, porosity, compressibility, diffusion parameters (tortuosity, effective diffusion coefficients) and retardation parameters. Except for porosity, each of these physical properties in a particular core sample has a different value depending on the orientation of the sample in the testing apparatus. In standard practice, the direction of the test sample is the same as the core long axis (i.e., the K is measured along the long axis of the core rather than across the core so that, for example, K_v is determined from cores from vertical holes). Measurements of the core physical properties discussed below are commonly done in commercial laboratories operating on charge per sample basis and, except for the diffusion parameter, the laboratories use well established methods.

Measurement Principles and Methods

The K of the core sample is obtained from Darcy's Law based on the rate of water flow through the saturated core sample under an imposed hydraulic gradient. During the test, the sample is contained in an apparatus known as a triaxial cell, which imposes stresses on the samples to represent the field stress conditions. For unlithified aquitards the compressibility of the sample is sometimes measured in the same apparatus, or in a different apparatus known as a consolidometer or odometer, also capable of providing K values.

Three different methods are available for porosity measurements on rock core samples: gravimetric, mercury porosimitry and scanning electron microscopy (SEM). The first two methods are readily available from commercial laboratories. For aquitard cores, the gravimetric method is easiest and generally preferable in the context of aquitard investigations.

The effective diffusion coefficient (D_e) is a parameter specific to each contaminant, however the measured parameters (formation factor, D_e tracer) used to estimate contaminant-specific D_e values are more general. The formation factor (F) is measured by applying electrical current across the core sample. Several commercial laboratories in North America do this measurement. The measurement of D_e tracer is done (using chloride as the tracer) in only one commercial laboratory (Golder Associates, Mississauga, Ontario; contact person Dr. Frank Barone). The values for D_e for each contaminant of interest are obtained from F and D_e tracer using calculation procedures described by Parker et al. (1994).

The retardation factor (R) for common dissolved organic contaminants (e.g., chlorinated solvents, benzene, toluene, xylene) is commonly obtained using a calculation that requires measured values for the fraction of organic carbon (f_{oc}), which is the weight per cent of solid-phase organic carbon in the sample. Several commercial laboratories conduct f_{oc} measurement using a procedure in which the inorganic carbon in the sample is destroyed by acid leaching and then the organic carbon is determined on the remaining carbon.

Advantages

Coring of aquitards is generally done primarily to assist in the determination of the geologic features and origin of the aquitard. However, an added benefit of coring is the acquisition of samples suitable for measurement of physical properties of representative core segments. The physical properties considered here are those relevant to calculations or modeling of groundwater flow and contaminant migration through aquitards. The core parameter values are applicable in the assessment of unfractured aquitards and, in the case of fractured aquitards, the core parameter values represent the matrix blocks between fractures. Most aquitards are comprised of more than one textural or lithologic zone (strata) and therefore there is usually need to conduct parameter measurements on samples from representative parts of the aquitard. The core samples provide parameter values orientated in the direction of the core hole (generally vertical or near vertical), which is the most important direction in the context of water flow and contaminant migration. The directionality aspect of core measurements is advantageous because nearly all other measurements pertaining to the drilling location (e.g. packer tests, bore hole flow metering, geophysical logging) are biased towards the formation properties orthogonal to the borehole (i.e., typically the horizontal direction).

Data Expected

Depending on the investigation goals and /or budget limitations, the parameters measured and the number of samples subjected to each measurement will be different from project to project. For example, K and porosity are essential parameters for many projects but measured diffusion parameters are less essential. Useful D_e and R values for the contaminants of concern can sometimes be estimated from literature values through comparisons of the aquitard of interest to aquitards previously investigated.

Limitations

One of the major issues in most investigations of aquitard integrity is the determination of whether or not fractures are an important feature. The measurements of physical properties of core samples does not accomplish this determination on its own because the probability of any of the cores having active fractures is small. Fractures generally occur at a spatial scale (i.e., spacing) that is large relative to core size. Therefore, to address the issue of fractures, and to make major use of the core data, field tests using boreholes and wells must also be conducted.

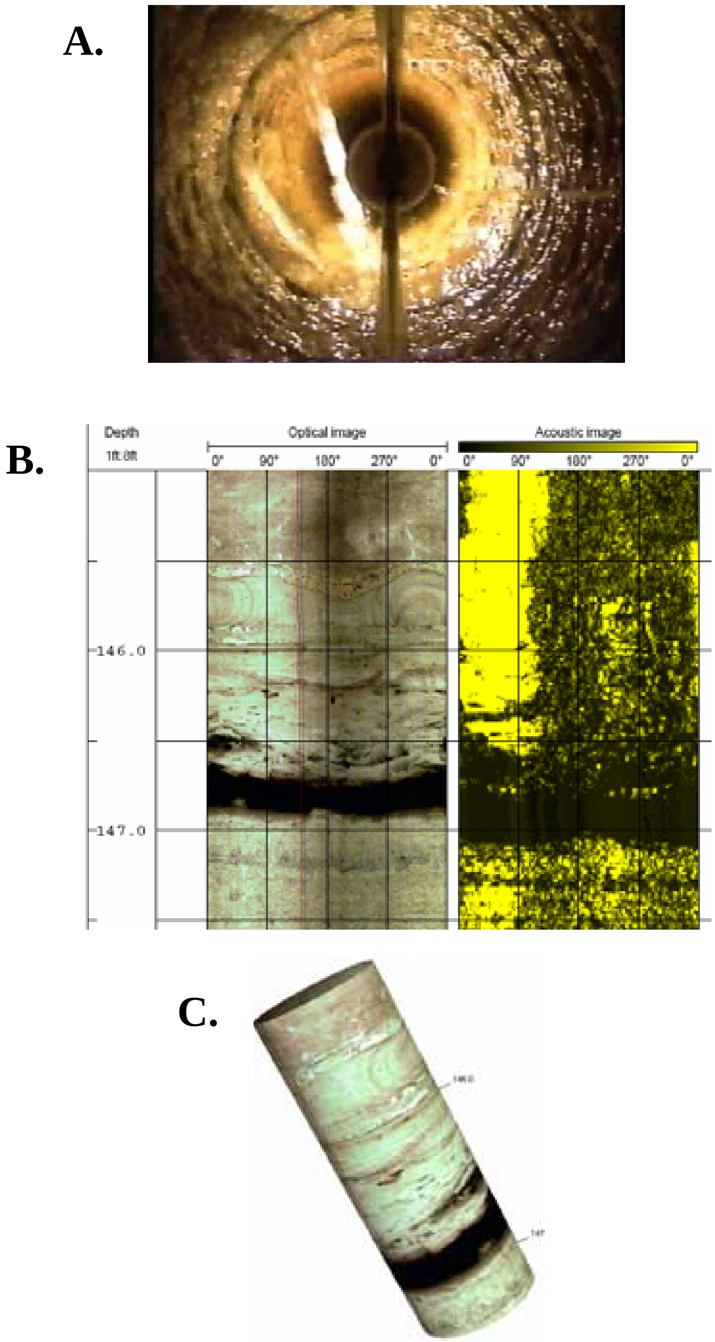


Figure 5.1 Examples of borehole imaging. A: borehole television image of water flowing from a fracture in the borehole wall; B: digital optical (left) and acoustic (right) images of bedding features and an open fracture; C: virtual core reproduction of the optical image in B.

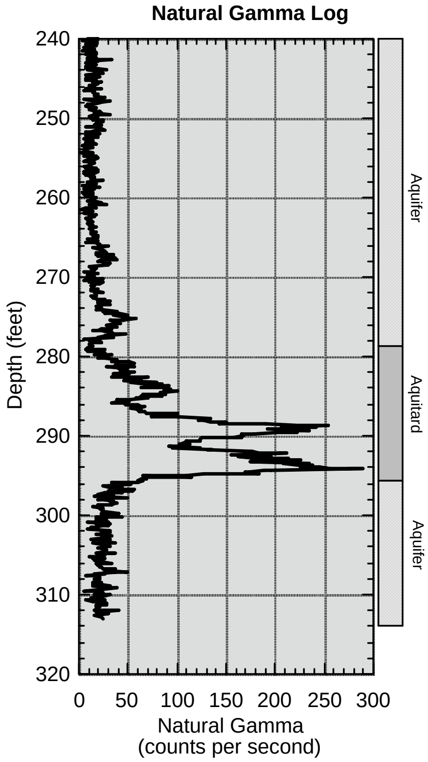


Figure 5.2 Natural gamma log showing an aquitard bounded by aquifers above and below. The Eau Claire shale is overlain by the Wonewoc sandstone and underlain by the Mt Simon sandstone at well NS-1 at the Nine Springs site.

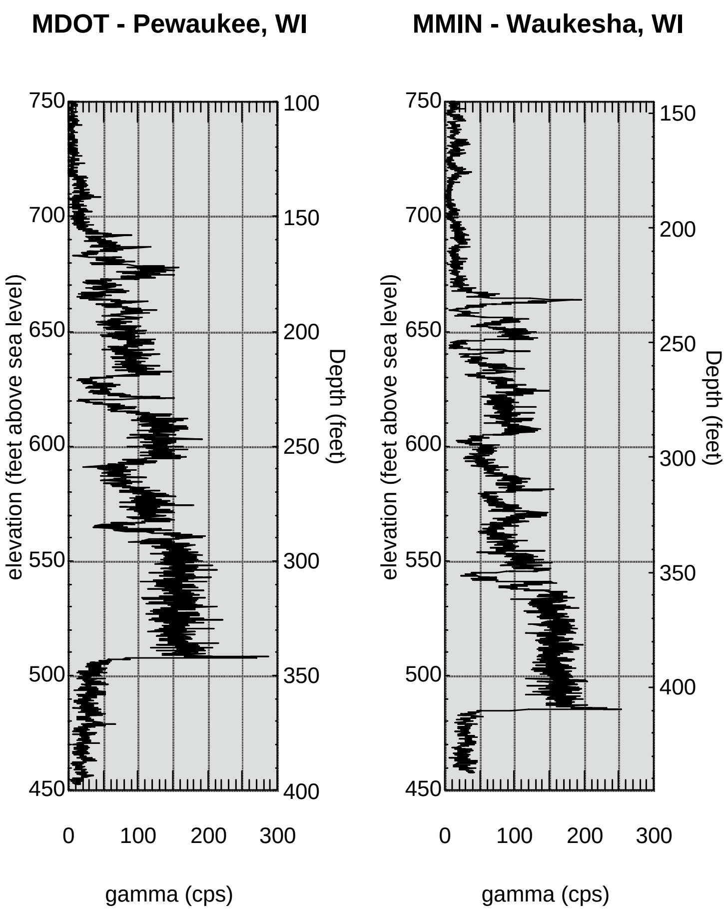


Figure 5.3 Natural gamma logs located approximately 6 miles apart in southeastern Wisconsin. The logs indicate similar lithologies at the two boreholes. A thick, massive shale sequence in the Maquoketa Formation in the MDOT well (a depth of 290 to 340 feet) correlates to the MMIN well (a depth of 360 to 410 feet).

Figure 5.4 Diagram of a normal resistivity probe with electrode spacings of 8, 16, 32, and 64 inches.

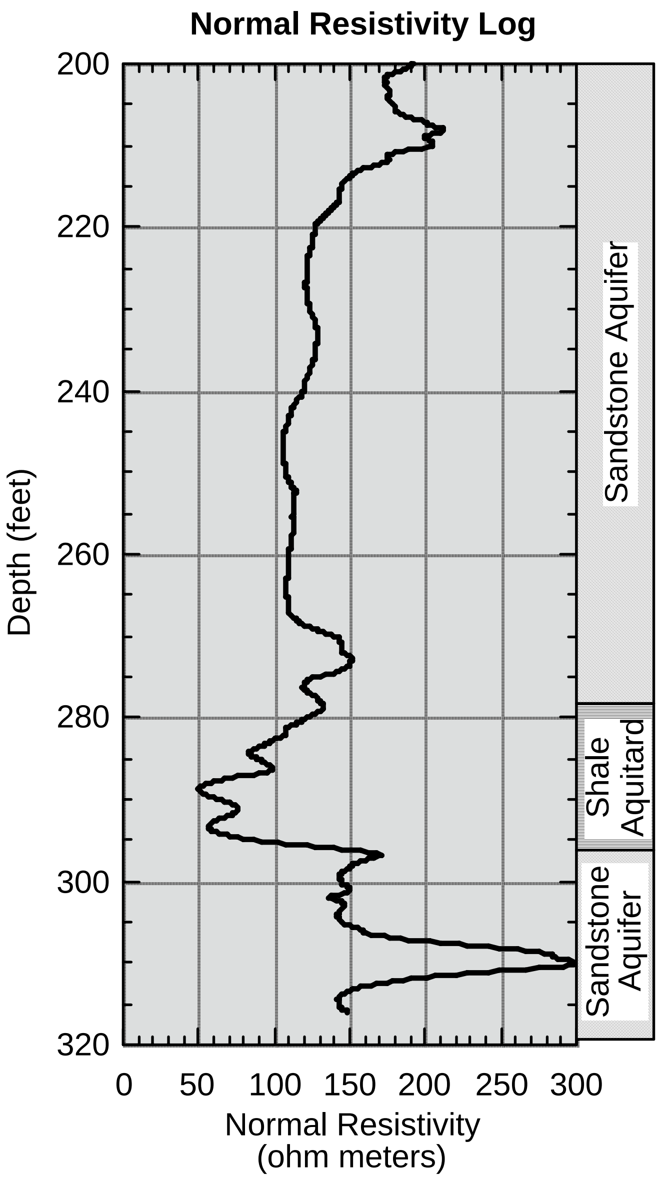
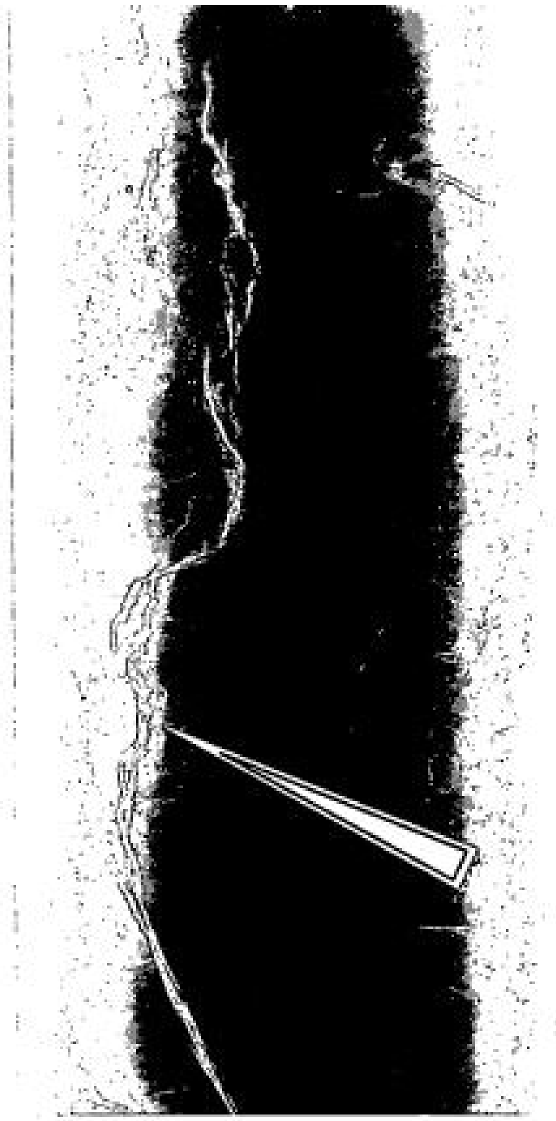


Figure 5.5 Normal resistivity log showing an aquitard bounded by aquifers. The Eau Claire shale is bounded by the Wonewoc sandstone above, and the Mount Simon sandstone below. The peaks in the log at 208 and 310 feet correspond to well-cemented portions of the sandstones.



Source: PPG (1995).

Figure 5.6 X-radiograph showing open fracture in a clayey aquitard.

CHAPTER 6
TESTING AND SAMPLING FROM OPEN BOREHOLES

This chapter includes several methods used to evaluate flow within an open borehole. These methods are generally restricted to lithified settings because of the requirement for an open, uncased portion of a borehole. A majority of the measurements collected yield qualitative indicators of vertical gradients or identify portions of the borehole that contribute flow to the well. As such, they are useful to distinguish between areas of aquifer and aquitard in *multi-aquifer wells* or to make comparisons between wells completed in similar hydrogeologic units.

PACKER TESTING IN BOREHOLES

Operating Principle

Packer testing refers to the use of expandable packers inside open boreholes to isolate portions of the borehole for hydraulic testing or water sampling. Packers usually consist of a rubber bladder covering a rigid metal or plastic core. In use, deflated packers are suspended at desired depths in a borehole using pipe, cables, or drill rod. Packers are usually inflated by pressurized gas or fluid supplied from the surface. Once inflated, the packers seal against the borehole wall and prevent fluid movement up or down the borehole. Packers are commonly arranged in pairs so as to isolate the borehole interval between the two packers (Figure 6.1). This arrangement is called a *straddle*. A passage through the packer core allows access to the straddled interval for hydraulic testing and head measurements (Figure 6.2). For example, standard slug tests can be conducted to estimate K_h of the packed interval.

Advantages

Packer testing in open boreholes using straddle packers allows depth-discrete measurement of K_h and, in favorable circumstances, hydraulic head (Chapter 8).

Data Expected

Packer testing yields K_h and head data focused on the straddled interval, which can commonly range from less than one foot to tens of feet. In the context of aquitard studies, smaller intervals will typically yield more insight into the hydrogeologic properties of the aquitard.

Relevant Hydrogeologic Setting

Packers can be useful in most hydrogeologic settings where open boreholes are available and where formations are mechanically stable. Their use becomes more difficult and expensive as borehole depths and diameters increase.

Limitations

Packers require open, and generally uncased boreholes. Packers for small-diameter (2-4 inch) boreholes are relatively light and can be handled by 1or 2 people with manual equipment. Packers for larger (6-inch and greater) diameter holes are heavy and usually require mechanized hoisting equipment. Packer testing can be a slow process when testing low-K formations such as aquitards – a single test might require 1 to 2 days.

Cost

A wide variety of packer equipment is commercially available, and many commercial contractors can do packer testing. Minimum equipment costs range from about $1000 for small-diameter equipment to $10,000 or more for large diameters. Contracted testing can usually be carried out for several hundred dollars per test plus mobilization charges.

Companion Tools

Packer testing should be planned and conducted in conjunction with subsurface data obtained from geophysical logs and drilling records.

Site-specific examples

General references for packer testing include http://toxics.usgs.gov/pubs/FS-075-01/; Shuter and Pemberton (1978), and Zeigler (1976). We provide examples of K_h measurements and a vertical profile of hydraulic head collected during straddle packer testing of the Eau Claire aquitard at the Nine Springs field site in chapter 8 and Appendix A.

GROUNDWATER SAMPLING USING STRADDLE PACKERS

Relevant Hydrogeologic Setting

Straddle packer systems can be used to obtain groundwater samples from specific depth intervals in open boreholes in lithified materials.

Operating Principle

The equipment used for straddle packer sampling, which consists of two inflatable packers with groundwater samples drawn from the open interval between the packers, is similar and in some cases identical to that used for K testing of open boreholes in rock (previous section, Figure 6.2). The straddle packer assembly is lowered down the open borehole to the desired depth, the packers are pressurized and groundwater is pumped from the zone between the packers. After a period of pumping intended for purging, the water sample is collected.

Advantages

Straddle packer systems can be easily assembled or obtained from contractors for holes in the diameter range of 3 to 7 inches and, because the systems are used only for a short period of time (hours to days) in each hole, the costs are generally much less than for sampling using a depth-discrete multilevel system. However, as described below, we do not recommend the use of straddle packer testing for determination of groundwater chemistry, including natural hydrochemistry and contaminant occurrence in fractured sedimentary rock.

Limitations

When boreholes in rock are open, vertical flow occurs upward and/or downward between fractures or across aquitards. This *hydraulic cross connection*, which is unavoidable during the time when the borehole is open, causes mixing of the groundwater chemistry and isotopic concentrations in the borehole and in the formations alongside the borehole. Therefore, when water is pumped using the packer system, the samples represent disturbed water that may or may not represent the formation water as it existed prior to drilling the hole. Although some believe that stabilization of field measurements of temperature, pH and electrical conductance during purging can provide evidence of removal of the disturbance effects, there is still much uncertainty even if these parameter values stabilize with time. This is particularly the case for fractured sedimentary rocks, where matrix diffusion effects can greatly increase the purging time needed to remove cross connection effects from the groundwater (Sterling et al. 2005). Therefore, although described here, we do not recommend the use of straddle packer testing in fractured sedimentary rock for determination of groundwater chemistry, including natural hydrochemistry and contaminant occurrence.

FLUID TEMPERATURE AND ELECTRICAL CONDUCTIVITY LOGS

Relevant Hydrogeologic Setting

Fluid temperature and electrical conductivity logs require an uncased borehole and are therefore most often useful in lithified formations.

Operating Principle

The fluid temperature and fluid resistivity are recorded continuously as the measurement probe is lowered through the borehole. Fluid resistivity is the inverse of fluid conductance, and is a measure of the electrical resistance of the fluid. This provides an indirect measure of the concentration of dissolved solids in the fluid. The profile of temperature and resistivity may show abrupt changes where there are areas of discrete inflow or outflow into the borehole. These logs can be used in conjunction with a caliper log to identify fractures that produce groundwater. Temperature and conductivity are two distinct properties, but they are described in one section in this report because they are typically collected with a probe that provides simultaneous measurements.

In its more simple form, temperature and resistivity logging are performed in a borehole that is at equilibrium conditions (that is, when it has been purged of drilling fluid and the groundwater in the borehole reflects flow into the well under the equilibrium site gradients). Temperature and conductivity logging may also be performed as part of an injection test, whereby the borehole water is replaced with deionized water and a series of fluid resistivity logs are collected over time as the well is pumped. Formation water flows into the well through more conductive zones and fractures under pumping conditions. The formation water is of higher conductance than the deionized water, resulting in peaks on the resistivity logs where formation water flows into the well. This method has a trade name of Hydrophysical logging, and is described by Tsang et al. (1990). Tsang et al. (1990) use the method to calculate fracture transmissivity.

Advantages

Fluid temperature and resistivity logs can be used to identify fractures that produce water.

Data expected

A continuous record of fluid temperature and fluid resistivity in a borehole.

Limitations

Does not measure properties of an aquitard, but does lend insight into which formations have hydraulically active fractures.

Cost

On the order of several thousand dollars per borehole to run a complete suite of standard geophysical logs including fluid temperature and fluid resistivity.

Companion Tools

Natural gamma, caliper, formation resistivity

Examples

Well DN1440 is open to the Wonewoc sandstone aquifer, the shale aquitard within the Eau Claire Fm., and the Mt. Simon sandstone aquifer (Figure 6.3). Distinct breaks in the fluid temperature and resistivity logs occur at depths of 192 and 228 feet. The caliper log shows increases in borehole diameter at these depths, supporting the conclusion that these are the locations of water-producing fractures. These fractures are in the upper portion of the Eau Claire Formation, above the shale interval identified by peaks in the gamma log at depths of 235 to 250 feet.

A deionized water injection test was performed at the Nine Springs field site in Dane County, WI., located 9 miles east of well DN1440 (Figure A.1). The fluid conductivity profile collected while pumping from well NS-3 (Figure 6.4) shows areas of discrete inflow at 285 feet, 279 to 281 feet, and at 272 feet. This result is in good agreement with the heat pulse flowmeter log from NS-3 (next section). The fluid conductivity logging shows that the shale facies of the Eau Claire contributes no flow to the well relative to fractures or more conductive zones higher in the formation.

BOREHOLE FLOWMETER LOGS

Relevant Hydrogeologic Setting

Flowmeters are useful in the uncased portions of boreholes, typically used in bedrock formations.

Operating Principle

Flowmeters record the vertical flow rate and direction (up or down) within a borehole. Three methods are available. An electromagnetic (EM) flowmeter uses an electromagnet and two electrodes to measure the flow rate of the water, which is the conductor.

A heat pulse flow meter measures the travel time of a pulse of heat to calculate flow velocity in the borehole. The probe is lowered to a particular elevation of interest, flow is allowed to stabilize, and a pulse of heat is triggered at the center of the tool. Two heat sensors (thermistors) are mounted on the tool, above and below the heating grid. A computer software program is used to record the arrival time of the heat pulse at either thermistor and convert it to a flow rate. The heatpulse flow meter is calibrated, but the readings of flow rate are influenced by the seal between the tool and the borehole wall.

Another type of flowmeter, the spinner flowmeter, is operated by trolling up or down a borehole. The rate of spinning of the meter is converted to a flow rate. The spinner flow meter requires higher velocities, and may not be as useful as the high-resolution heatpulse flowmeter in aquitard studies.

Advantages

Flowmeters can be used to determine the direction of natural (non-pumping conditions) vertical gradients within a borehole, identify portions of the borehole that contribute to flow under pumping and non-pumping conditions, and in some cases can be used to identify discrete, water-conducting fractures. Flowmeter results may indicate the direction of flow across an aquitard.

Data Expected

Measurements of vertical flow that indicate areas of in-flow and outflow along a borehole under natural or pumping conditions. Paillet (1998, 2000, 2001) provides examples of qualitative and quantitative analyses of heat pulse flow logs.

Limitations

Flowmeters measure net flow in a borehole; results do not always provide the resolution necessary to identify discrete fractures. While the method may provide an indication of a water-producing fracture, this depends on the fracture aperture where it insects the borehole. Thus, the same fracture a foot away could have a different aperture and would yield a different result with this method. Flowmeters readily yield qualitative differences between low and high permeability zones, but quantitative analysis of these logs may be complex.

Cost

On the order of several thousand dollars to hire a consultant with equipment and expertise to collect a flow meter log. This is most cost-effective when collecting a full suite of borehole geophysical logs.

Companion Tools

Flow logging may be performed along with borehole geophysics (Chapter 5).

Site-specific Examples

Heatpulse flowmeter logs were collected under pumping and static conditions in a well at the Nine Springs research site in Madison, WI (Figure 6.4). The static log shows increasing downward flow from 270 to 280 ft, indicting flow into the well from the formation. The reduction in flow rate to zero at a depth of 290 ft suggests that flow goes into the formation above the shale facies (the shale is apparent in the gamma log from 289 to 296 ft). The static log shows that natural gradients are downward at this location from the Wonewoc aquifer across the Eau Claire aquitard. The log demonstrates that multi-aquifer wells open across the aquitard provide a pathway for flow and transport from the upper to the lower aquifers, across the aquitard.

The flowmeter log collected under pumping conditions shows no flow from the base of the borehole to 285 ft. Above this depth, the flow is increasing upwards, with step-increases occurring at depths of 284, 280, and 272 ft. The step-increases in flow suggest the presence of water-bearing fractures at these depths, or may bound short intervals of aquifer with higher permeability. The maximum flow rate that could be used without overwhelming the response of the flow meter (which depends on the borehole dimensions, and in this case was 1.9 gallons per minute) did not exceed the capacity of the upper portion of the well. Therefore, there was no measurable contribution to flow into the well below a depth of 285 ft during this test.

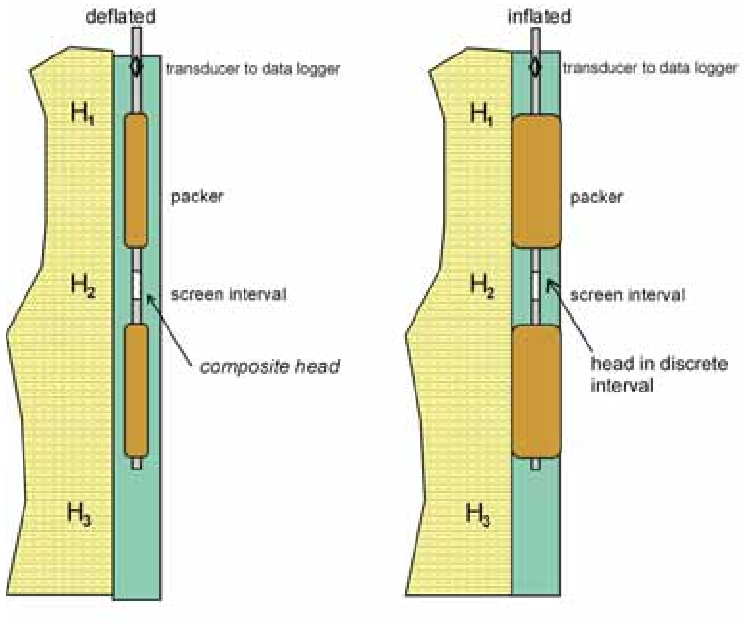


Figure 6.1 Straddle packers. (a) with packers deflated, head measured in screened interval is the composite head from the length of the borehole, across H_1, H_2 and H_3. (b) with packers inflated, head measured within the screened interval is the head at H_2.

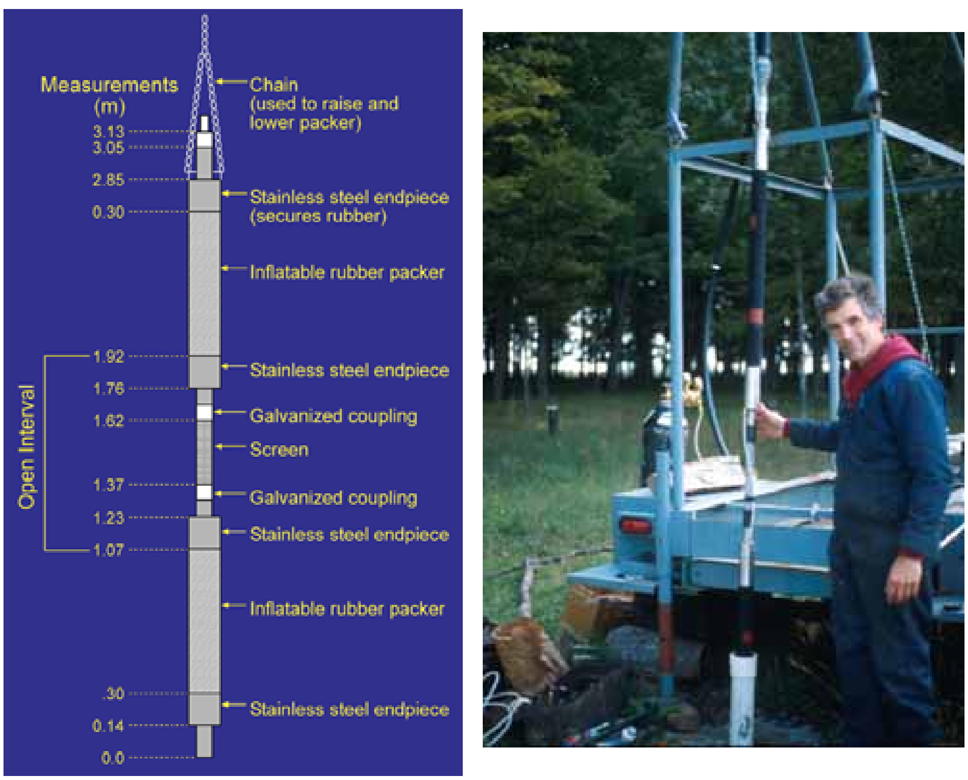


Figure 6.2 Lightweight packer equipment for use in small-diameter wells.

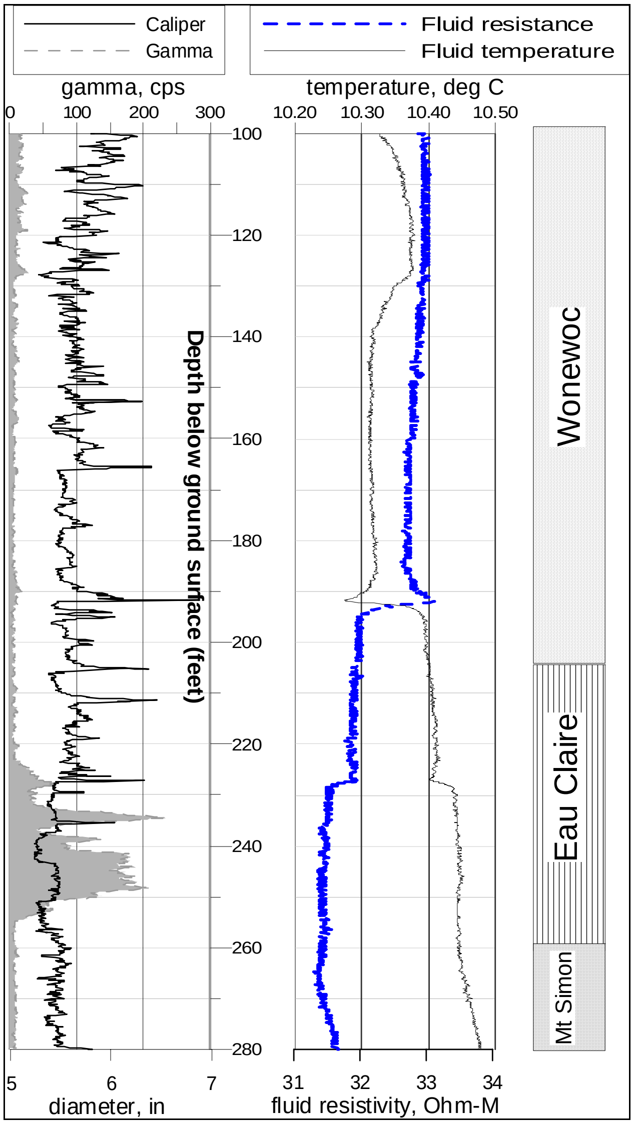


Figure 6.3 Gamma, caliper, fluid temperature and fluid resistivity logs from well DN1440.

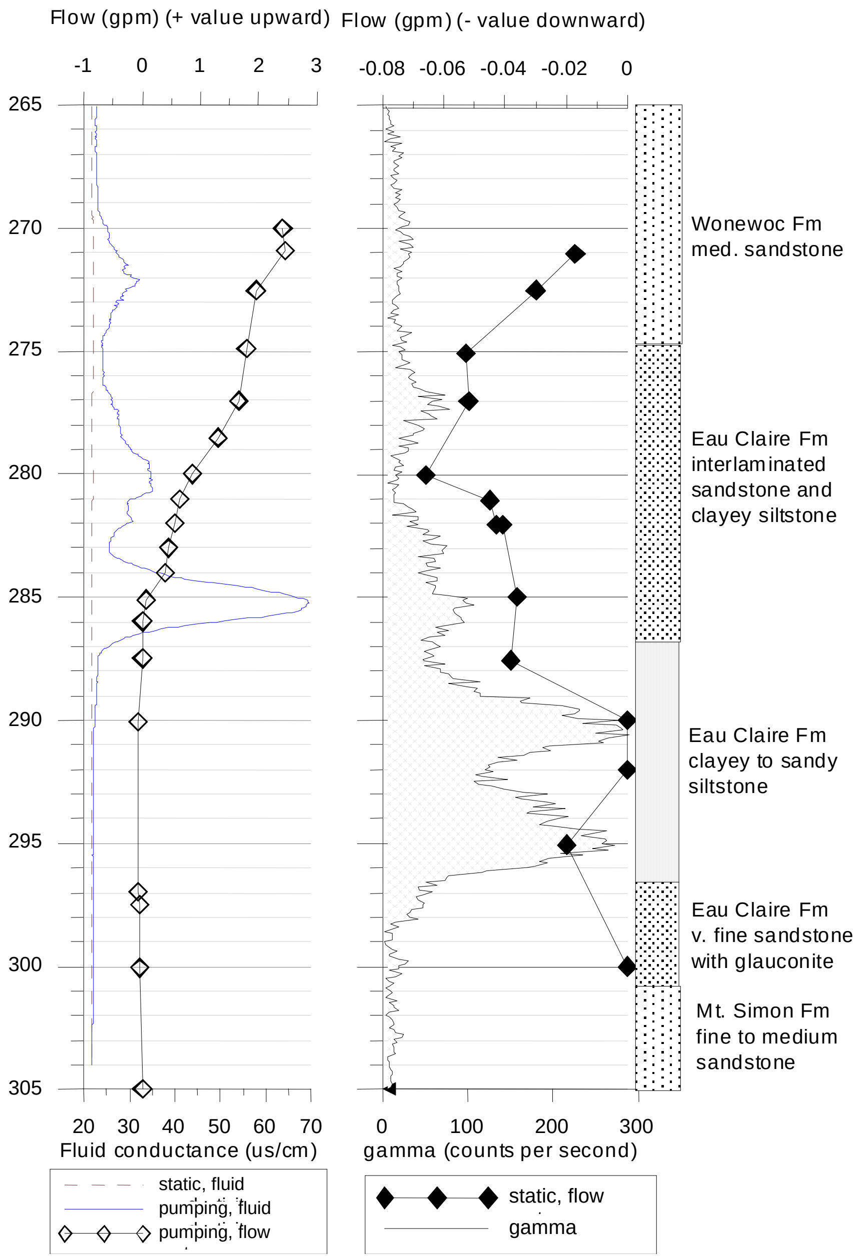


Figure 6.4 Borehole logs from well NS-3 at the Nine Springs site. Fluid conductivity during a fluid injection test and heat pulse flow meter results under pumping conditions are shown to the left. Heat pulse flow meter results under static conditions and the gamma log from the well are shown on the graph to the right.

CHAPTER 7
BOREHOLE INSTRUMENTATION

Aquitard studies that focus on a specific well, well field or contamination site should include profiles of hydraulic head and/or water quality across the aquitard. Data requirements can vary from simple static head measurements to complete profiles of head variation over time and solute concentrations. Drilling and coring techniques are expensive; to make the most of this investment, the resulting open boreholes can be fully tested (Chapters 5 and 6). The information gained from testing the open borehole may be used to design the long-term instrumentation of the borehole. This chapter discusses techniques for borehole instrumentation that are intended to serve over the long-term and, most importantly, provide information about the vertical profile of hydraulic heads within an aquitard. Site-specific data sets collected from boreholes across a region can be used to understand variations across a regionally extensive aquitard, as is demonstrated in Chapter 10.

STANDPIPE PIEZOMETERS

Relevant Hydrogeologic Setting

Piezometers (monitoring wells constructed with very short screens or openings) can be installed in every hydrogeologic setting but may not always yield representative measurements or estimates of all parameters in all settings. For example, water levels in a piezometers installed in very low-conductivity clay formations can take on the order of weeks to months to equilibrate.

Operating Principle

A *piezometer* is a well constructed with a relatively short screen (on the order of 1 to 5 feet) that provides representative measurements at a point at depth in the subsurface. A piezometer instruments the interval of the aquitard or aquifer intersected by the length of screen and associated sand pack.

Several piezometers can be installed in a *well nest* of closely spaced boreholes completed to various depths of interest in the aquitard. In some cases, multiple piezometers are installed in a single, large-diameter borehole. Constructed in this fashion, the interval of the borehole between each screened interval must be carefully sealed (e.g. bentonite or equivalent grout) to isolate each monitored zone. Nested piezometers provide data similar to the vertical profiles obtained from multi-level monitoring systems; each piezometer provides a single point along the profile.

A longer screen (on the order of 10 feet) is installed where a well is intended to intersect the water table, because the depth of the water table is uncertain or seasonable variations in water levels are expected. Sand filter pack is usually placed between the well bore annulus and the screen to provide good hydraulic communication between the well and the formation. A seal, such as grout or bentonite, is emplaced between the well bore annulus and the well casing to isolate the well screen from the overlying formations. Piezometers may be designed somewhat differently in bedrock or fractured bedrock applications, where a screen and/or sand filter pack may not be necessary.

In general, water supply wells cannot be used in place of piezometers to characterize hydraulic conditions. Pumping from the well prevents obtaining head measurements representative of aquifer conditions. Supply wells are typically open to 10s to 1000s of feet of aquifer thickness. Measurements of head and water quality represent an average of the conditions along the open interval of the well. These averaged data provide useful information for characterizing aquifer conditions, but yield little insight into the properties of adjacent aquitards.

Advantages

Piezometers are easy to design and construct; many drillers are experienced in their installation. As long as the well seal is carefully emplaced during well construction, there is little uncertainty associated with the long-term performance of piezometers, compared to the maintenance required for some packer systems and risk of failure of buried transducers. It is simple and inexpensive to measure water levels, conduct slug tests, and collect water samples from piezometers.

Data Expected

Data obtained from piezometers include water-level measurements and groundwater samples. A pressure transducer and data logger may be used to automate long-term water level monitoring or monitoring during a pumping test. Slug tests conducted in piezometers are analyzed for estimates of K_h (Chapter 8).

Limitations

The greatest limitation of a piezometer is that it provides access to only one depth in the subsurface. The cost of drilling multiple boreholes to install nested piezometers typically exceeds the cost of outfitting a single borehole with a multilevel monitoring system.

Cost

Materials and labor to install a piezometer in an existing borehole range from about $10 to $15 per foot, excluding the cost of drilling. Costs vary depending on depths and the type of materials used.

Example

Standpipe piezometers are installed at depths that instrument an aquitard and adjacent aquifers (Figure 7.1). In this example, water levels, or hydraulic head, in the upper aquifer are higher than in the lower aquifer. The associated head profile shows a significant decline in hydraulic head across the aquitard.

BURIED TRANSDUCERS

Relevant Hydrogeologic Setting

Buried transducers can be useful in most hydrogeologic settings where formations are mechanically stable and open boreholes are available. Pressure transducers can also be buried in unlithified materials at depths that can be penetrated using DP and HSA drilling. The use of buried transducers becomes more difficult and expensive as borehole depths and diameters increase.

Operating Principle

A series of pressure transducers installed inside a single borehole is used to measure head profiles in aquitards and aquifers. In this technique, several transducers are placed in the same borehole at the depths of interest, often just above, inside, and just below the aquitard, and then buried (Figure 7.2). Usually, a short gravel pack is placed around the transducer to provide hydraulic contact between the transducer and the formation. The transducer and gravel pack are sealed in place and isolated from the other transducers with a cement-bentonite grout or a solid bentonite seal. A data logger at the ground surface records transducer response.

Advantages

Buried transducers allow depth-discrete measurements of hydraulic head. They provide a permanent seal and a long-term head measurement system that requires minimal maintenance. If installed properly, there is little danger of a system failure providing a pathway for contaminants. The well has essentially already been abandoned during the buried transducer installation. Installation of buried transducers is inexpensive and relatively simple. The materials and techniques used to create the seals between the buried transducers are similar to those used to abandon wells. Thus, the knowledge and materials used to create the seals are readily available.

Data Expected

Buried transducers measure the groundwater pressure, which is converted to hydraulic head, at a discrete depth. A series of buried transducers yield vertical profiles of increases and decreases in hydraulic head along the length of the borehole. Buried transducers connected to a data logger provide head measurements through time (for example, as conditions change due to pumping or variations in recharge).

Limitations

Buried transducers are permanent and if one fails after installation, it cannot be repaired. Likewise, it is not possible to recover the transducers after the grout or bentonite has set. The borehole is not available for or other testing (e.g., groundwater sampling, packer tests, borehole geophysics) after installation. Transducers cannot be checked for drift after installation. Although vibrating wire transducers are less likely to drift than strain gage transducers, the possibility remains that a gradual change in transducer readings is due to instrument drift, rather than to changing water levels. Lightening strikes, anthropogenic electrical effects that occur in industrialized areas, and methane gas, can cause transducers to fail. Finally, regulatory agencies may not approve of borehole abandonment with the transducers in place.

Cost

The cost of a single vibrating wire transducer ranges from $500 to $1000, depending on the length of cable needed. The cost of bentonite chip to provide seals is about $3 per foot for a 6-inch diameter well. Purchase of a suitable data logger is on the order of $1,000 to $2,000. Labor costs may be high: an installation of 11 transducers in a 300-foot deep, 6-inch diameter borehole took three days to complete, following drilling.

Companion Tools

Before installation of buried piezometers, borehole geophysics should be conducted to determine optimal depths of burial for the transducers. The lithologies and thicknesses of the aquifers and aquitards should be identified before installation.

Site-specific Examples

Data from NS-1 at the Nine Springs field site is shown in Figures 7.3 and 7.4. These show the head profile from a set of buried transducers and the heads as a function of time. The variation in head over time is caused by pumping from a municipal well located 1000 feet from the transducers and from barometric loading and recharge. Eaton and Bradbury (2003) used buried piezometers to measure and record a head profile in the Maquoketa shale in southeast Wisconsin.

DEPTH-DISCRETE MULTILEVEL MONITORING SYSTEMS

Background

Depth-discrete multilevel monitoring systems are installed in boreholes to monitor discrete zones at several or more depths below ground surface. These devices provide profiles of hydraulic head or water chemistry versus depth. The term ‘depth-discrete’ refers to the fact that each monitoring interval, or “zone”, is isolated by some type of seal from the zones above and below it. Other types of multilevel monitoring devices exist that are not depth-discrete. These systems are used to sample water at various depths in the open borehole, however they are not recommended for use in aquitard investigations because flow down or up the borehole (i.e. hydraulic cross connection through the borehole) can cause these devices to provide erroneous or misleading results. In this report, the term ‘multilevel monitoring system’ (MLS) denotes a depth-discrete system of hydraulically isolated zones, as indicated above.

Multilevel devices are essential tools in many aquitard investigations because their use is more cost effective than installing nests of standpipe piezometers or wells. Nested wells require drilling several separate holes close together at a location, as described in a previous section. In this approach, the drilling costs commonly are prohibitively high.

In recent years, a diversity of MLS’s have been developed for purchase commercially from manufacturers. In each site application, the commercial system is tailored to the site hydrogeology through specifications of a number of components and dimensions within the available options.

Relevant Hydrogeologic Setting

With proper selection of drilling methods and multilevel system design, multilevel systems can be installed in all types of hydrogeologic settings. In boreholes that stand open after drilling, such as occurs in some surficial clayey aquitards and in many types of bedrock, the drilling rig need not remain over the hole while the multilevel system is installed. In unstable holes, drill casing is withdrawn from the hole as the multilevel system is installed to prevent cave-in from interfering with proper positioning of the MLS ports and seals. There is no limitation to the maximum depth to which multilevel systems can be installed. Monitoring at great depth (> 1000 feet below ground surface) can be accomplished when the appropriate selection of multilevel system and drilling method is made.

Design Options, Installation and Versatility

Four types of multilevel systems are available commercially. Although they all can accomplish hydraulic head monitoring and water sampling at each monitoring zone, they differ in design and materials. The first MLS to enter the commercial marketplace, in the late 1970's, was the Westbay MP system available from Westbay Schlumberger Inc.: www.westbay.com;. The Waterloo System (late 1980's) is available from Solinst Canada Limited: www.solinst.com. In the 1990's two more systems became available: the Flexible Liner Underground Technology (FLUTe™) groundwater system: www.flut.com and the Continuous Multichannel Tubing (CMT) system available from Solinst Canada Limited. In 2004, the Waterloo System, initially developed primarily for use in bedrock, became available in a modified design particularly suited for use in studies of unlithified aquitards (Parker et al. 2005).

The *Solinst*™ Waterloo systems are available with permanent or removable packers. The packers are inflated or expand after installation to isolate each zone. *Solinst*™ CMT system relies on sand pack and seals installed around a central stem of tubing to create isolated zones. The CMT design allows for up to seven ports and is best suited for shallow water table applications. The Westbay system uses a series of packers and valved port couplings within the casing. Portable tools are lowered down the casing and connected to each port to collect measurements and samples. The FLUTe™ system relies on a coated fabric sock that seals against the borehole wall by maintaining a high water level inside the sock. Ports cuts into the fabric provide access to the formation and groundwater through tubing that extends to the well head.

Prior to the late 1990's, MLSs were used primarily in bedrock investigations. More recently, due to the widespread availability of rotosonic drilling equipment and the introduction of the CMT and modified Waterloo Systems, depth-discrete multilevel monitoring can be accomplished in unlithified deposits to depths on the order of 200-300 ft. Rotosonic drilling advances steel casing while taking continuous core. The MLS (either a FLUTe™, Waterloo or Westbay system) is then lowered down inside the casing. The casing is withdrawn gradually as sand packs are emplaced around the ports (screened intervals) and seals of bentonite or grout are emplaced above each sand pack. Thus, each monitoring port has hydraulic connection via the sand pack to the formation. A pressure transducer can be connected to each port for continuous monitoring of head, or measurements may be collected manually.

Although other types of drilling equipment (e.g. hollow stem augers, direct push, mud-rotary) are suited to unlithified deposits, rotosonic drilling is preferred for installation of MLSs in unlithified deposits for several reasons. Rotosonic drilling avoids use of mud (which can clog the formation), facilitates accurate placement of sand packs and seals, and advances holes through nearly all types of unlithified deposits (even through boulders) and into bedrock.

The commercial availability of the four types of MLS and the major differences in basic design/materials of these systems allows tailoring the MLS to various overall data needs and site-specific conditions. The MLS can be designed and installed to facilitate easy removal after a specified monitoring period of months or years (e.g. the FLUTe™ system), or the system can be installed with the intention of monitoring over decades (e.g. the Westbay and Waterloo systems). In bedrock, MLSs can be installed in existing wells if the well consists of open rock below the base of the casing. At many bedrock sites such wells exist and should be considered for retrofitting using a multilevel system (wells with long open intervals are susceptible to cross-connection effects that yield them ineffective for measuring head or water quality profiles).

It is not uncommon for MLSs to be installed in holes in which a casing with multiple well screens is installed first. In this approach, a hole of six-inch diameter or greater is drilled in the overburden or bedrock and a casing is installed with multiple segments of well screens with blank casing between the screens. The screens are positioned at zones for which monitoring is desired, sand packs are emplaced around the screens, and bentonite or grout seals are emplaced around the blank casing segments. Thus, standard drilling and well construction methods are used to accomplish the installation of the multi-screen casing. This approach has been used at many sites for various reasons, such as facilitation of eventual MLS removal, facilitation of borehole abandonment, and allowing the installation of an MLS to proceed without the aid of a drill rig.

Advantages

A commercially available MLS is almost always the most cost-effective means to obtain depth-discrete profiles of hydraulic head and/or water sampling at more than two or three depths in each hole. The four types of commercially available MLSs provide a wide spectrum of options and costs to meet nearly all monitoring specifications. The only alternative to use of MLSs is nested piezometers or use of straddle packer measurements at different depths in single holes. However, straddle packers do not provide head records over time for multiple depths, nor do they produce depth-discrete hydrochemical data representative of ambient conditions in the formation (because of the prohibitively large purge volumes typically necessary to minimize borehole cross connection effects). Thus, for hydrochemical data acquisition, straddle packer testing is not an alternative to use of MLSs.

Limitations

In some cases, there can be uncertainty about the integrity of the seals between the ports in MLSs. This concern is generally avoided by selection of the most appropriate MLS for the particular site conditions and careful installation of the system in each hole.

Cost

There are three cost categories associated with installing a MLS at a site: drilling the borehole, purchasing the MLS, and installing the MLS. The complete cost of these three components for a single MLS ranges from $10,000 to $200,000 for depths of about 50 to 500 feet. The lower-end of this range is representative of the cost of purchasing an MLS without dedicated pressure transducers or dedicated sampling pumps, to depths on the order of 50 to 100 ft. Purchase and installation costs for two MLSs (one with six ports to a depth of 310 ft and one with four ports to a depth of 160 ft) with dedicated pressure transducers at the Nine Springs research site totaled $45,000.

Site-specific Examples

The MLS installed at the Nine Springs field site provided data for a profile of hydraulic head with depth (Figure 7.5). The MLS measures a 20-foot drop in head over the five-foot shale sequence at the base of the aquitard. The response to pump cycling in a near-by municipal well is reflected in the head measurements collected over time with the pressure transducers installed within the MLS.

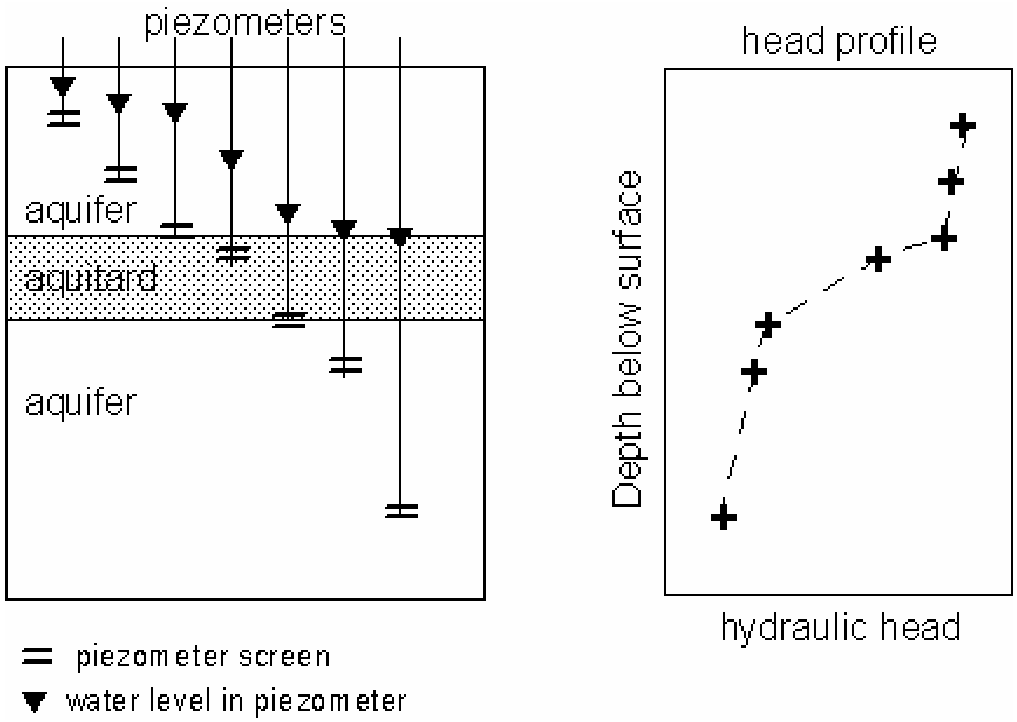


Figure 7.1 Conceptual head profile through an aquitard using standpipe piezometers. Left: piezometer locations. Right: head profile.

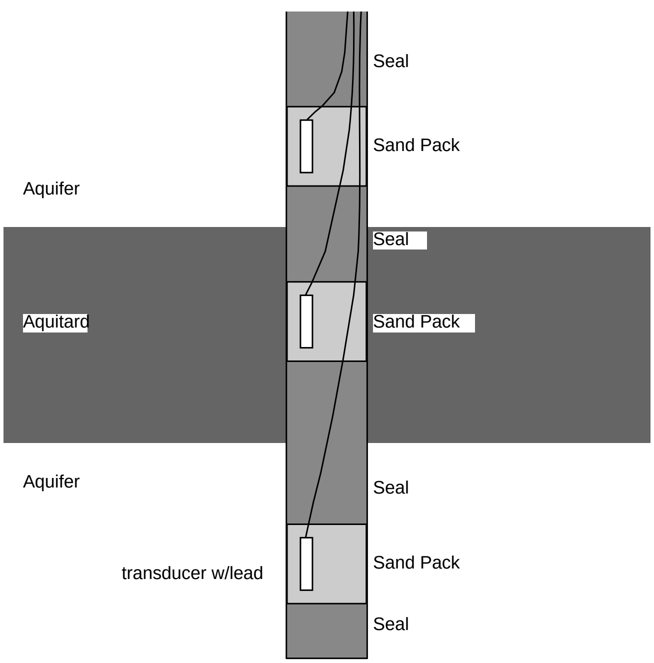


Figure 7.2 Schematic of installation of buried transducers.

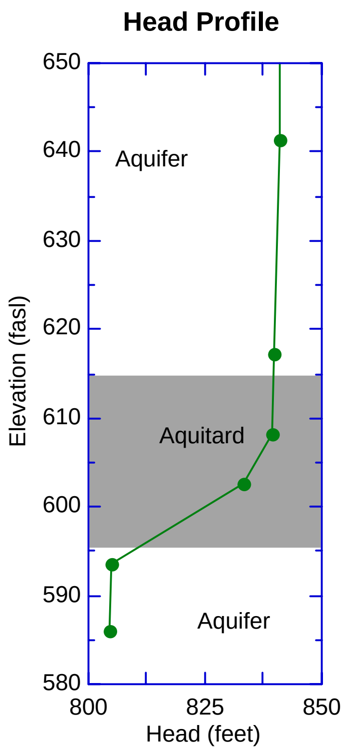


Figure 7.3 Head profile from buried transducers in NS-1 at the Nine Springs site.

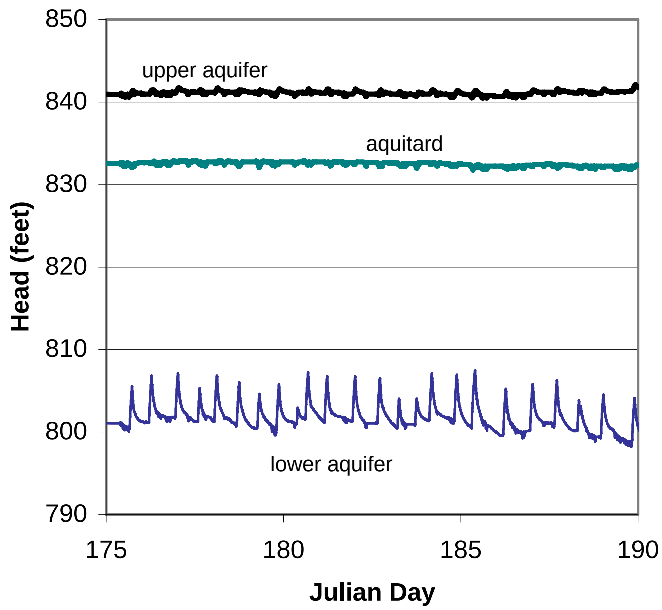


Figure 7.4 Variation in heads over time from buried transducers at the Nine Springs site. The variation of heads in the lower aquifer is due to pumping from nearby municipal well.

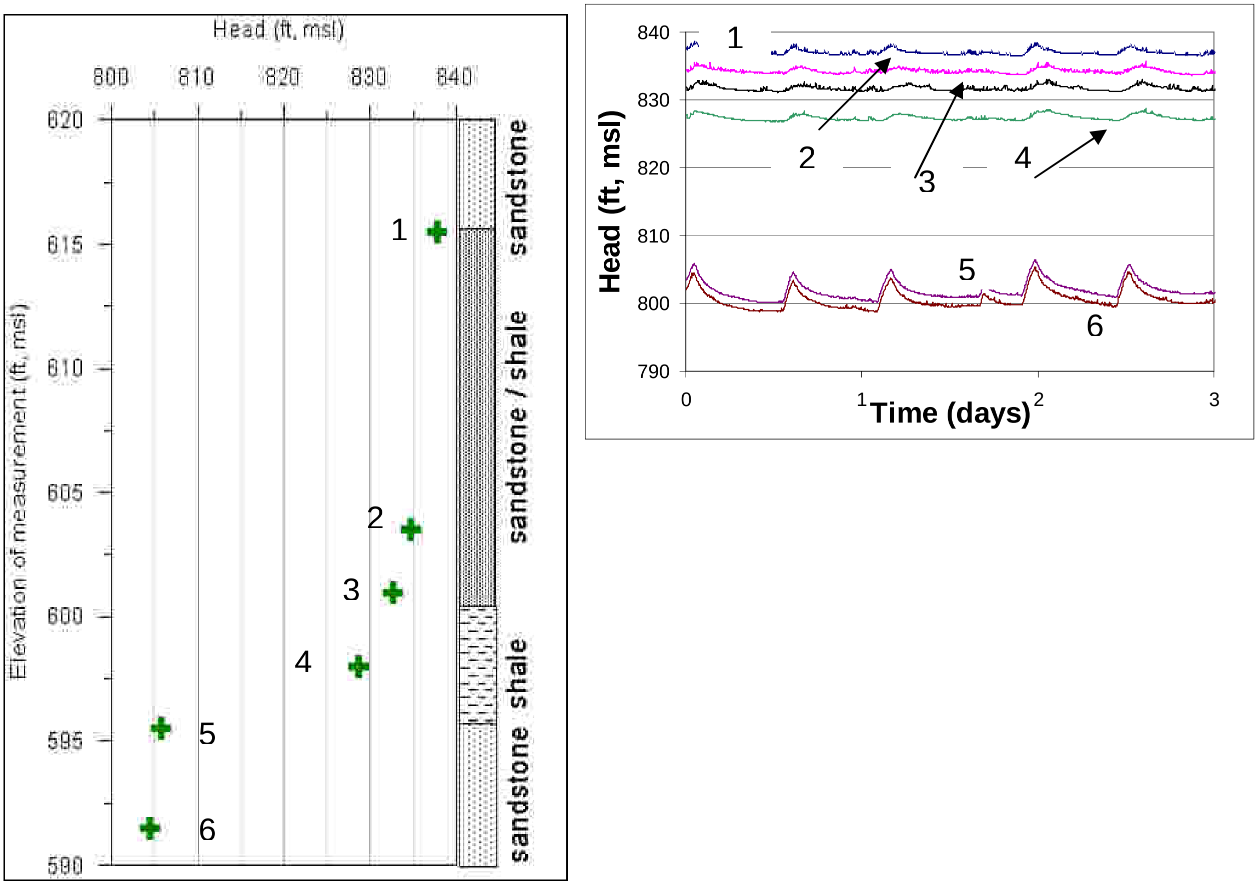


Figure 7.5 Head profile from multilevel monitoring system installed at Nine Springs site (left) and the head profile recorded over time (right). Numbers indicate the port of the MLS that the measurement was collected from. The vertical profile of static head measurements shows a very large decrease in head (about 25 ft) over about two feet of the borehole (from 598 to 596 feet). This indicates that a only a small portion of the aquitard (the thick shale facies) supports the high hydraulic head above the aquitard.

CHAPTER 8
ESTIMATING THE HYDRAULIC CONDUCTIVITY OF AQUITARDS

The K_v of an aquitard is a fundamental parameter controlling groundwater flow and contaminant transport through the aquitard. All flow and transport calculations, from the most simple analytical equation to complex computer simulations, require values of K_v. Some analyses lump K_v together with aquitard thickness, and this lumped parameters is called *leakance*, expressed as K_v divided by the aquitard thickness.

Measuring the K_v of aquitards can be extremely difficult for several reasons. First, aquitards often occur deep beneath the land surface, so direct measurements must be made in wells or boreholes. Second, these wells and boreholes are almost always oriented vertically, or nearly so, while most aquitards are horizontal. Consequently, an individual well or borehole can sample only a small section of an aquitard. Furthermore, the flow of water into or out of a near-vertical well is nearly horizontal and is not the appropriate direction for testing the K_v of the formation. Third, aquitards by definition have low K, so the response time of field tests can be very long (days or weeks). In addition to these challenges, small heterogeneities, such as fractures and macropores, and larger heterogeneities (windows) can greatly influence the bulk properties of an aquitard, yet are often difficult to detect with wells.

This chapter describes several methods for estimating K_v in aquitards. We recommend starting with regional estimates of K_v based on available data. These estimates can be refined using measurements collected from site-specific field testing of an aquitard and numerical modeling efforts.

ESTIMATING VERTICAL HYDRAULIC CONDUCTIVITY FROM A MAPPED CONE OF DEPRESSION

Operating principle

This method applies to an aquifer that is bounded above and below by aquitards. A pumping well completed in the aquifer will cause water levels to decrease in the aquifer. If the well is pumped for a long enough time, the water levels will stop decreasing and will remain relatively constant and are said to have reached a steady state. We assume that the water levels approach constant values because the decrease in water levels in the aquifer causes additional water to flow from across the upper aquitard. This additional flow, or "leakage", from the upper aquitard into the aquifer prevents the water levels in the aquifer from continually decreasing. Figure 8.1 shows a profile view of a *cone of depression* that would form around a pumping well beneath an aquitard at steady state. If many wells are located beneath an aquitard, forming a regional pumping center, then a regional cone of depression forms around that pumping center. Figure 8.2 shows the regional cone of depression in southeastern Wisconsin.

The steady state solution of the Hantush-Jacob (Hantush 1956) leaky aquifer test may be used to estimate the upper aquitard K_v at local and regional scales, given a cone of depression, an estimate of the aquifer transmissivity, the thickness of the upper aquitard, and the pumping rate.

Advantages

The steady state solution of the Hantush-Jacob leaky aquifer test provides a quick, easy way to estimate the K_v of an aquitard. The required information for the analysis: a cone of depression, an estimate of the aquifer transmissivity, the thickness of the aquitard, and the pumping rate, are often readily available for both local and regional aquitard investigations. Furthermore, the calculation does not require a computer or any specialized analysis or modeling software. Although the method has practical limitations, it provides an estimate of K_v that may suffice in some instances. The method is more useful when site-specific information is available to determine the source of the steady-state leakage. Our description here assumes the leakage is from across the upper aquitard.

Data Expected

An estimate of K_v of the aquitard.

Relevant hydrogeologic setting

For this test to be applied, the water levels should be at steady state, a measurable cone of depression must have formed, and the pumping rates, aquifer transmissivity, and the aquitard thickness must be known.

Limitations

This method assumes that the source of flow to an aquifer is water flowing across a single aquitard, but there are other hydrogeologic conditions that can supply “apparent leakage” to an aquifer that underlies an aquitard. Therefore, this is a “black-box” approach that assumes, rather than identifies, porous-media flow across an aquitard. In reality, flow and transport through aquitards is often dominated by heterogeneities such as fractures, macropores, or sand seams. This method does nothing to elucidate the hydraulic head changes within aquitards that can be diagnostic of these features; this “leaky aquifer” analysis ignores the relative importance of these features to flow and contaminant transport through the aquitard. Assumptions in this analysis include that the aquitard and aquifer are infinite in horizontal extent with no variation in thickness or conductivity; the aquifer is bounded below and leakage to the aquifer is through the overlying aquitard, the pumping rate is constant, and water levels are at a steady state.

When some or all of these conditions are not met in reality, this analysis yields only a first-cut approximation of the K_v of a regionally extensive aquitard. Violations of these conditions result in cones of depression that are not circular in shape, and result in fluctuating (non-steady-state) water levels. If there are issues regarding aquitard integrity that are site-specific, this method is not applicable; detailed analysis of the ground water flow system is best provided with methods such as monitoring heads and water quality *within* the aquitard, conducting a pumping test, and constructing a calibrated flow model.

Cost

The costs for this method are minimal, personnel time only, if the required information is available.

Companion tools

This method is only a first step in determining the role of the aquitard in protection of the underlying aquifer. It requires information typically available at the beginning of an aquitard investigation and gives an estimate of aquitard K_v. This initial estimate can be used to shape the conceptual model of the flow system that includes the aquitard and aquifer(s). The analysis should be refined at later stages of an investigation with data collected from installing piezometers (or equivalent monitoring systems) within an aquitard. This first-cut estimate of K_v should not be used in place of local-scale hydraulic tests.

Examples

An example calculation of the K_v of an aquitard is shown below. A regional cone of depression has formed in southeastern Wisconsin due to pumping beneath the Maquoketa shale aquitard. This cone of depression is shown in Figure 8.2. Relatively impermeable Precambrian rock forms the bottom boundary to the aquifer. The maximum drawdown has exceeded 450 ft in the center of the cone of depression. The western edge of the Maquoketa shale aquitard is shown as the bold line to the west. This cone of depression is not circular due to absence of the aquitard to the west. The length of the arrow is 20 miles and water levels have decreased by approximately 350 feet at its tip due to pumping.

We can apply the steady state Hantush-Jacob solution (Fetter 2001) to this cone of depression.

$$s = \frac{Q}{2\pi T} K_0(r/B)$$

$$B = \sqrt{\frac{Tb'}{K'}}$$

where s is drawdown, Q is the regional pumping rate, T is the aquifer transmissivity, K_0 is the zero-order modified Bessel function of the second kind, r is the radius from the pumping center that the drawdown is measured, b' is the aquitard thickness and K' is the aquitard K_v. We wish to ultimately determine K' so we first solve for $K_0(r/B)$, then using Figure 8.3 (a graph of Bessel functions) or a table of Bessel functions (available in many hydrogeology texts) we find the ratio, r/B, that corresponds to the $K_0(r/B)$. Finally, knowing r/B and all the values in B, except K' we can solve for K'.

The necessary parameter values are listed below. These values were determined from well records, water level maps, and pumping rate records.

Drawdown, s = 300 ft

Regional pumping rate, Q = 33 million gallons per day = 4.4 x 10^6 ft^3/day

Transmissivity of the aquifer, T = 2000 ft^2/day

Radius at which drawdown is measured, r = 20 miles = 105,600 ft.
Thickness of the aquitard, b' = 200 ft.

1. Solve for $K_0(r/B)$.

$$K_0(r/B) = \frac{2\pi sT}{Q} = \frac{2\pi \times 300\text{ft} \times 2000\ \text{ft}^2/\text{day}}{4.4 \times 10^6 \text{ft}^3/\text{day}} = 0.856$$

2. Determine the value of r/B that corresponds to the $K_0(r/B)$. Using the graph below, we can see that a value of $K_0(r/B)$=0.856 corresponds to a value of r/B=0.5.

3. We can rewrite the expression for r/B so that K' can be calculated.

$$r/B = r\sqrt{\frac{K'}{b'T}} = 0.5.$$

Substituting for the known values and solving for K' gives

$$K' = \left(\frac{\frac{r}{B}}{r}\right)^2 b'T = \left(\frac{0.5}{105{,}600\ \text{ft}}\right)^2 200\ \text{ft} \times 2000\ \text{ft}^2/\text{day} = 10\text{x}10^{-6}\ \text{ft/day}$$

This estimate is similar to the one determined by the regional groundwater flow model for southeastern Wisconsin of 5 x10^{-6} ft/day. The Hantush-Jacob value is larger than the groundwater flow model value, which we attribute to lack of steady state conditions and groundwater recharge to the aquifer from the west, where the aquitard is not present. Both of these factors would increase the calculated K_v above the actual value. This estimate, 10x10^{-6} ft/day, took less than a day to determine, while constructing and calibrating the regional groundwater flow model was the result of more than a year of effort.

HYDRAULIC CONDUCTIVITY MEASUREMENT USING SLUG TESTS

Operating Principle

The single-well displacement "slug" test is a simple technique for estimating K_h in the field using wells or piezometers. By measuring the response of a well or piezometer to a rapid pressure pulse, the investigator estimates K_h around the well screen or piezometer tip. To yield estimates of K_h of an aquitard, the elevation of the screened interval or the open borehole must occur within the aquitard.

Advantages

Slug tests are inexpensive and require minimal training or equipment. Data analysis is relatively simple. Can be conducted using straddle packers in boreholes (Chapter 6). In aquitard studies, slug test results may be compared to laboratory conductivity measurements made on samples of core. If the slug test values are significantly larger than the laboratory measurements, one explanation may be that fractures are present in the aquitard that increase the K_h calculated from slug tests.

Data Expected

Estimates of K_h unless the well is oriented horizontally.

Relevant Hydrogeologic Setting

Almost any hydrogeologic setting where the well or piezometer is in good communication with the formation to be tested.

Limitations

This method does not yield estimates of K_v. Well construction and geometry can highly bias results. For example, smearing of boreholes in unlithified deposits can cause lower K_h in the vicinity of the borehole compared to the undisturbed formation. These tests can be time-consuming in the low-conductivity geologic materials that constitute aquitards.

Cost

Minimal cost if borehole is available; several hours of time for a hydrogeologist to conduct test and analyze data.

Companion tools

Can be used in conjunction with straddle packers or some multilevel monitoring systems.

Site-specific Examples

Butler (1998) gives a comprehensive review of slug testing methods and analytical procedures. An example of the analysis is presented in the following section.

ANALYSIS OF DATA OBTAINED FROM STRADDLE PACKERS

Operating Principle

Simple measurements can be used to estimate K_h and hydraulic head in borehole intervals isolated by straddle packers. The total hydraulic head in the packed zone is measured after equilibration to borehole conditions. K_h can be measured using a simple borehole-response ("slug") test. Repeated measurements over a series of packer placements provide a profile of head and K_h through the formation. Pressure transducers attached to a data logger provide rapid and simple data acquisition. Slug test data can be interpreted using a variety of methods described by Butler (1998); many of these solutions have been implemented for automatic solution in commercially-available software such as AQTESOLV (Duffield 2002).

Advantages

Borehole tests are relatively inexpensive and require only a single borehole. The straddle packer assembly focuses the test in narrow stratigraphic intervals, and repeated tests can generate a vertical profile of hydraulic head or K_h. Although the data reflect conditions near the borehole and are generally considered small-scale tests, they can provide a useful check on K_h obtained from laboratory tests of core samples. A significantly larger value of K_h from a straddle packer test may indicate fractures or other heterogeneities that are not reflected in the laboratory measurements.

Data Expected

The raw data consist of water levels or pressures in the packed zone versus time. Data interpretation consists of static head measurements (head) and slug test analyses (K_h).

Relevant Hydrogeologic Setting

Useful in most hydrogeologic settings where open boreholes are available and where formations are mechanically stable.

Limitations

The resulting data are focused on conditions near the borehole and are generally considered small-scale tests. Such tests might not detect local aquifer or aquitard heterogeneity at larger scales. The tests yield K_h only and are relatively insensitive to K_v. Tests can be time-consuming; in low-K units each test might take one or more days.

Cost

A wide variety of packer equipment is commercially available, and many commercial contractors can do packer testing. Minimum equipment costs range from about $1000 for small-diameter equipment to $10,000+ for large diameters. Contracted testing can usually be carried out for several hundred dollars per test plus mobilization charges.

Companion Tools

Packer testing should be planned and conducted in conjunction with subsurface data obtained from geophysical logs and drilling records.

Site-specific Examples

Figures 8.4 and 8.5 show data obtained at the Nine Springs research site in Madison, Wisconsin. The vertical profile of static head measurements collected from the packed intervals (Figure 8.5) shows a very large decrease in head (about 35 ft) over one foot of the borehole (from 296 to 297 feet). This indicates that a only a small portion of the aquitard (the thick shale facies identified by the peaks in the gamma log) supports the high hydraulic head above the aquitard.

PUMPING TESTS FOR AQUITARD ASSESSMENT

Operating Principle

Pumping tests usually refer to the observation of water-level changes in one or more observation wells or piezometers while water is withdrawn from a nearby pumping well. Although pumping tests have historically been viewed as a quantitative tool for measuring the hydraulic properties (transmissivity, storage coefficient) of aquifers, their role in aquitard investigations is often significantly different. Unlike porous-media aquifers, flow and transport through aquitards is often dominated by heterogeneities such as fractures, macropores, or sand seams. Hydraulic head changes within such features can be diagnostic of the presence of these features and of the relative importance of these features to flow through the aquitard. Typically, the primary goal of aquitard pumping tests is to determine whether preferential pathways (e.g., fractures) are present. Another goal is to determine the K_{bv}, however, the critical issue is determining whether or not the K_{bv} is governed by porous medium or fractured medium response.

Advantages

Pumping tests generally stress larger volumes of earth material than smaller-scale tests (e.g. straddle packers or laboratory tests on core samples), and so can provide information over areas ranging in size from tens to thousands of square feet. In addition, the sometimes unpredictable patterns of drawdown in aquitard pumping tests, for example greater drawdown at a distant observation point than a point near the pumped well, offers incontrovertible proof of hydraulically-connected subsurface heterogeneities. The advantage provided by pumping tests with monitoring within the aquitard is that the piezometer does not have to be connected directly to the fracture to provide a response indicative of a fracture; the pore-pressure response will propagate away from each fracture to encompass ever-increasing zones of pore-pressure decline while the pumping test is in progress.

Data Expected

Pumping tests are a traditional method for investigating the hydraulic properties of aquifer/aquitard systems, however these tests require piezometers completed *within* the aquitard, in order to monitor the aquitard head response to aquifer pumping. In aquitards with no fractures, all piezometers away from the aquitard/aquifer contact will show a slow response to pumping. In fractured aquitards, any piezometers situated on or close to fractures will have a fast response to pumping compared to piezometers in the aquitard that are situated away from fractures. Pressure transducers installed in aquitards can also be used to monitor response to rainfall or snowmelt, which can indicate presence or absence of fractures.

Relevant Hydrogeologic Setting

These tests may be useful whenever water levels are measured above, below, and in the aquitard. In addition, the pumping well should located near enough to the measuring points so that the pumping affects water levels in those wells.

Limitations

Pumping tests are not useful where the medium pumped (either aquifer or aquitard) cannot produce enough water to sustain a steady pumping rate. Detection and/or confirmation of fractures using pumping tests depends on observation points being located in appropriate places or depths.

Cost

Pumping tests costs can range from a few thousand to tens of thousands of dollars, depending on the scope of the test and facilities available. Costs are lower where monitoring wells are already instrumented to record head profiles and a pumping well is located nearby. Conversely, installing and operating pumping and monitoring wells can be quite expensive.

Companion Tools

The pumping test can usually be conducted using the same aquitard monitoring wells that are used to measure the head profile. In the case of aquifers studied for municipal well protection, very often a nearby municipal well can be used for the pumping well. The location of a pumping well should be considered when looking for a site at which to place the monitoring wells. Because pumping tests are often non-unique, it is necessary to have knowledge of the surrounding hydrogeology.

Examples

Grisak and Cherry (1975) describe a pumping test in a surficial clayey aquitard in which many piezometers were used to collect head measurements internal and external to the aquitard. They concluded that the much larger aquitard K_v determined from the pumping test was caused by vertical fractures penetrating from the water table down through the aquitard, which provided hydraulic connection with the underlying aquifer. Grisak et al. (1976) illustrate that some of the piezometers in the aquitard responded quickly to pumping and others did not. This indicates that some piezometers were situated on or near fractures and others were in the matrix blocks between fractures (Figure 8.6).

HYDRAULIC CONDUCTIVITY ESTIMATES FROM NUMERICAL MODEL CALIBRATION

Operating Principle

In appropriate situations, numerical groundwater flow models can produce estimates of aquitard properties through model calibration. Often, for subsurface aquitards, the desired field measurements of key parameters such as K_v are not available, yet the general geometry of the aquitard can be determined from existing borings and well logs. Aquitards are a key part of groundwater flow systems, and their hydraulic properties must be consistent with other observable flow system properties, such as water level distributions above and below the aquitard, recharge rates, and groundwater fluxes. Local- or regional-scale groundwater flow models can be powerful tools for assessing aquitard properties if sufficient calibration data are available, usually in the form of water-level measurements in existing wells completed in adjacent aquifers. Anderson and Woessner (1992) discuss methods of model construction and calibration, including automated inverse calibration methods.

Advantages

Numerical estimates of hydraulic properties can be inexpensive compared to field testing, and the models generally provide estimates of K_v over large areas. Numerical models also provide estimates of parameter uncertainty and the sensitivity of the groundwater flow system to variation in K.

Data Expected

Numerical modeling codes such as MODFLOW (McDonald and Harbaugh 1988) can generate either areal values of K_v of the aquitard, or lumped parameters such as leakance (K_v divided by aquitard thickness). Through a series of sensitivity analyses it is often possible to develop measures of the uncertainty of these estimates.

Relevant Hydrogeologic Setting

This method is only applicable where a numerical model exists or is being constructed and where sufficient water-level data are available for model calibration. The estimates should be considered lumped values adequate for regional studies of flow, drawdown, and aquifer vulnerability but not appropriate for site-specific studies of contaminant transport.

Limitations

The model-produced parameter estimates are lumped and averaged over large areas and might miss local heterogeneity or aquitard windows. In some cases the model solution might be relatively insensitive to aquitard properties and the estimates can be quite uncertain. Often, field verification of parameters is difficult.

Cost

Numerical modeling codes such as MODFLOW are widely available for low cost. Most costs will be in professional expertise and in acquiring calibration data. These costs vary widely from project to project.

Companion Tools

Numerical modeling is usually a part of modern hydrogeologic investigations and can often be used to guide the collection of field data. For example, a regional model might help indicate areas where obtaining site-specific aquitard data would be of most value.

Site-specific Examples

Krohelski et al. (2000) constructed a regional numerical model for Dane County, Wisconsin. This model included the Eau Claire aquitard as a model layer between upper and lower aquifer layers. Because the aquitard is thin (0-60 ft) and has no surface exposure, actual measurements of its hydraulic properties were nonexistent when the model was developed. Existing well logs provided data about its lithology, thickness and extent. Krohelski et al. assigned an initial K_v of 6 x10^{-4} ft/day to the aquitard based on literature values for similar materials. Based on model calibration (DCRPC 2001) the K_v estimate was increased slightly to 7.2 x 10^{-4} ft/day using hydraulic heads in over 3000 domestic wells as calibration targets. This model-produced estimate of K_v of the Eau Claire aquitard is useful to assess advective flux of conservative (non-retarding) solutes across the aquitard and their dilution in the underlying aquifer. This estimate of K_v is not useful in characterizing the vulnerability of the underlying aquifer to migration of DNAPL or particulate contaminants, such as viruses.

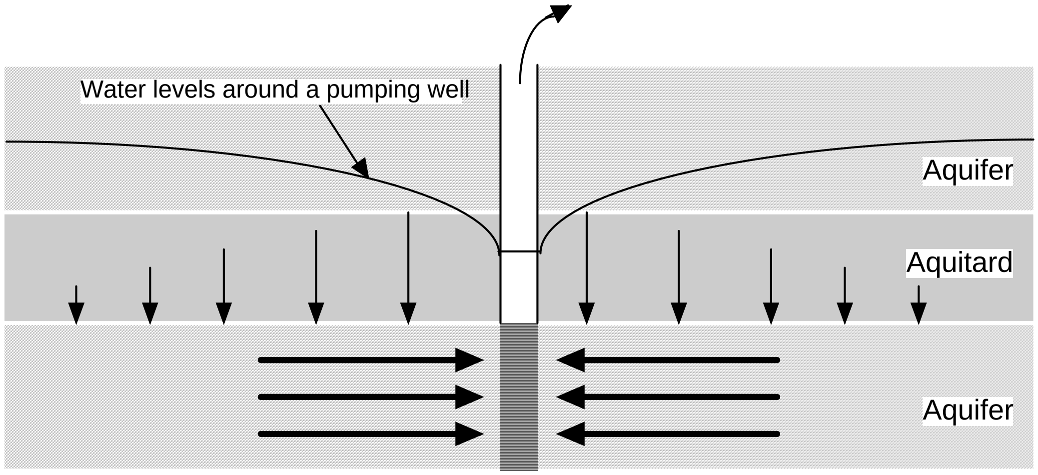
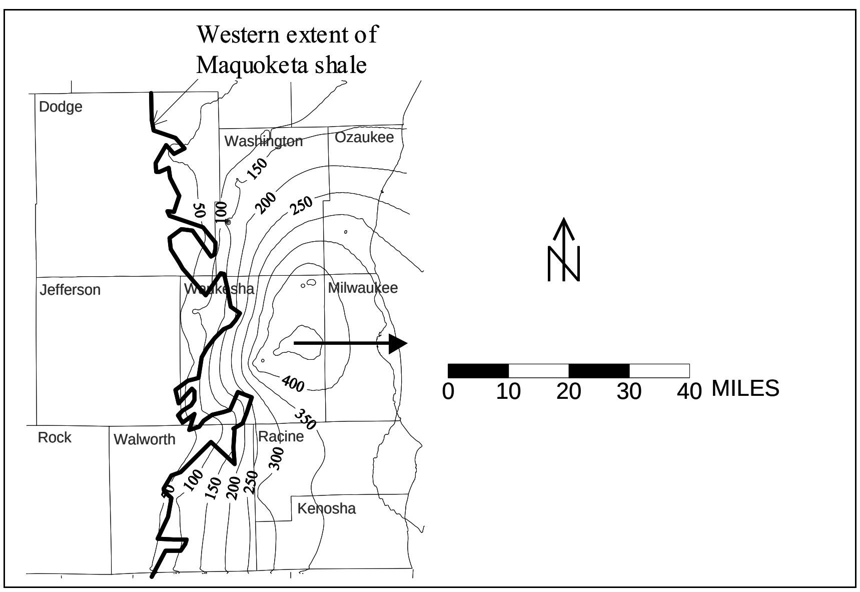


Figure 8.1 Profile of water levels (cone of depression) formed in a lower aquifer due to pumping in a well. The arrows shows the groundwater flow through the aquitard to the aquifer and from the aquifer to the well. This simple analysis assumes that there is no leakage upward from below the aquifer.



Source: Feinstein et al. 2004

Figure 8.2 Regional cone of depression in southeastern Wisconsin.

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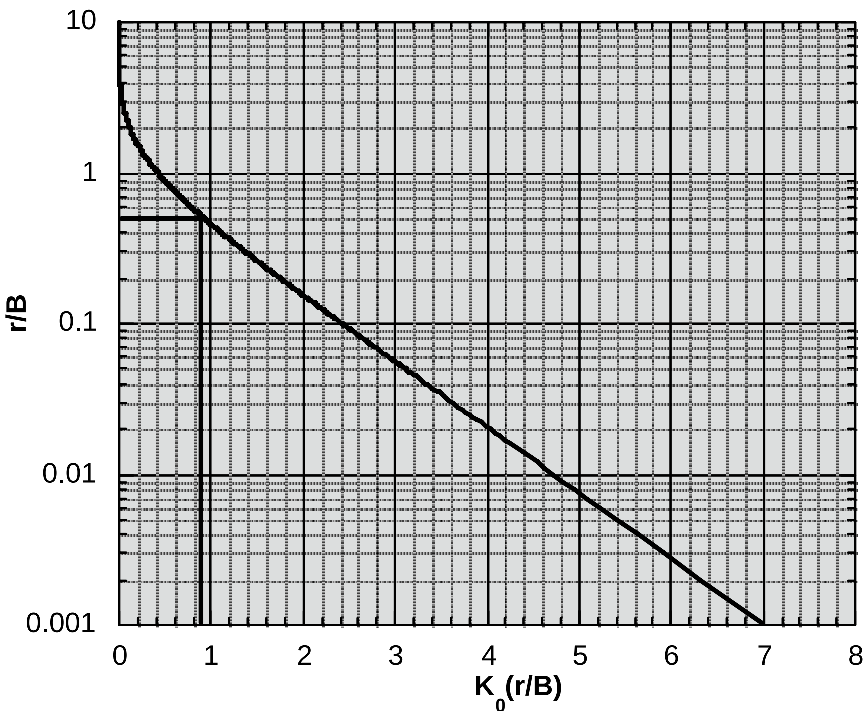


Figure 8.3 Plot of K(r/B) vs. r/B for use in the Hantush analysis of vertical hydraulic conductivity. Solid lines show values used in the example calculations.

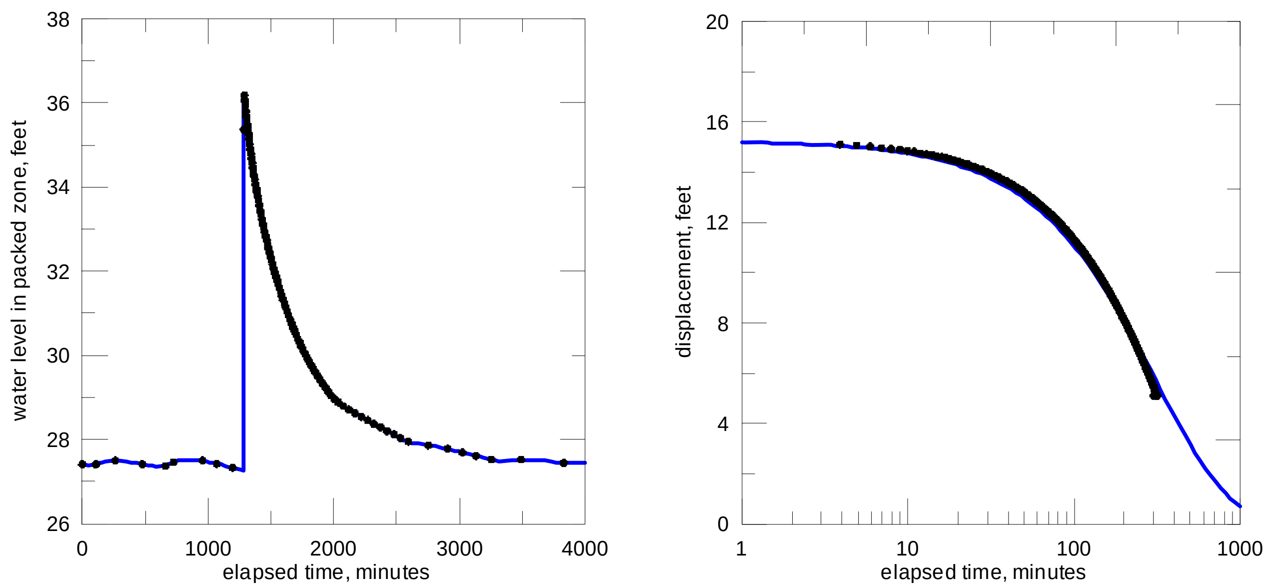


Figure 8.4 Example data from slug test using straddle packers. Left: raw data collected during test; baseline represents stabilized head in packed zone, displacement at 1200 min results from adding a volume of water to packer standpipe. Right: semi log plot of slug test response fitted to slug test type curve.

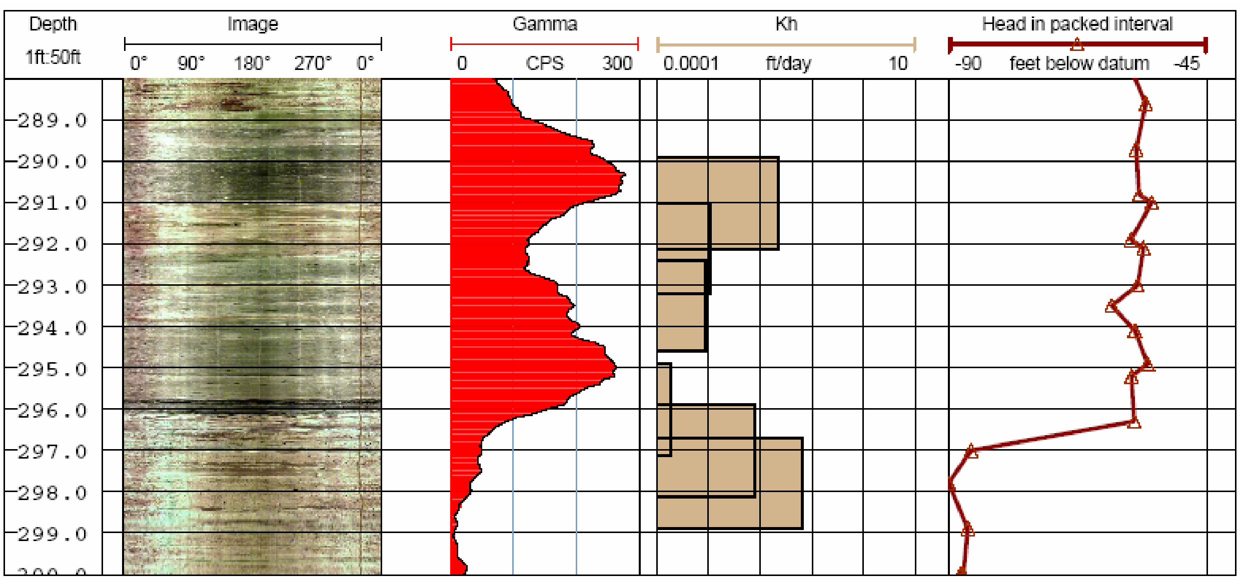
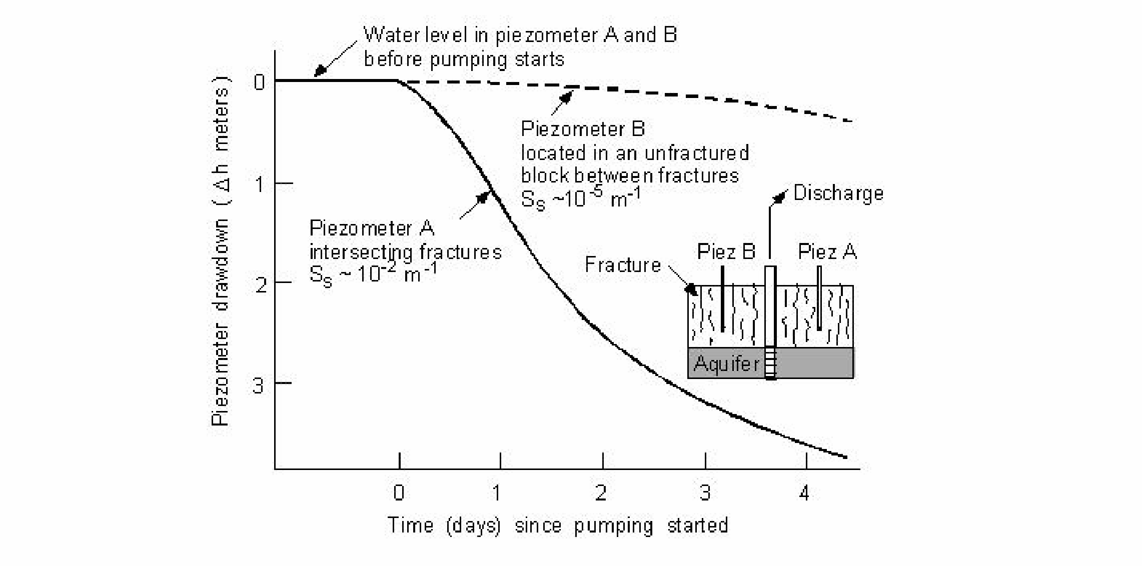


Figure 8.5 Example results from packer-slug test on well three at the Nine Springs site. Left image shows digital optical image of aquitard (289-296.5 ft). Bars show estimates of K_h derived from slug tests using straddle packers. Width of bars represents width of packed intervals. Right column shows static head measured in packed intervals.



Source: Grisak et al. 1976

Figure 8.6 Greatly different drawdown responses from two piezometers in a fractured aquitard during an aquifer pumping test: one piezometer (A) connected to a hydraulically active fracture shows rapid drawdown while another piezometer (B) not connected to a fracture shows almost no drawdown.

CHAPTER 9
ASSESSING CONTAMINANT TRANSPORT THROUGH AQUITARDS

In many, if not most, hydrogeologic studies involving aquitards the ultimate objective is to assess the transport of contaminants through an aquitard. Typical questions include the following:

1. How rapidly can water and/or contaminants move through the aquitard?
2. What contaminant concentrations occur within or below the aquitard?
3. What geochemical processes (degradation, sorption, precipitation, etc) occur within the aquitard?
4. How do heterogeneities (fractures, macropores, windows) in the aquitard influence water or contaminant movement?

This chapter outlines techniques for assessing transport through aquitards. The techniques include simple analytical estimates of flow rates, complex contaminant transport modeling, and chemical analyses of groundwater samples. Determining the concentrations of chemical constituents within aquitards usually requires a combination of water sample analysis and chemical analysis of geologic materials obtained from cores. Profiles of chemicals and isotopes obtained from water samples within aquitards provide indirect evidence of effective groundwater flow and transport velocities.

Understanding and predicting the transport of contaminants through aquitards is among the most challenging problems in hydrogeology because of the combination of measurement difficulties, geochemical transformations, and heterogeneity that is often present. Accordingly, here we recommend a combination of physical measurement and analytical and numerical modeling to address the questions posed above.

In particular, evaluating the role of fractures in contaminant migration across aquitards presents a technical hurdle for hydrogeologists. This stems from the nature of flow through fractured aquitards, which is distinctly different from flow through non-fractured aquitards. If fractures are absent from a clay or shale aquitard, transport processes will be dominated by molecular diffusion rather than advection. Models used to simulate these conditions should use a representative diffusion coefficient. An appropriate type of one-dimensional, diffusion-dominated model is demonstrated by Parker et al. (2004). If the aquitard is fractured, a discrete fracture model is necessary to simulate transport along these pathways. Models that assume porous media flow may yield erroneous results in these complex hydrogeologic settings. In this chapter, we provide the practitioner with several simple approaches to estimate transport in the simplest of hydrogeologic settings—transport through porous media. Caveats are provided where appropriate to caution application of these methods to more complex environments.

SIMPLE ANALYTICAL CALCULATION OF VERTICAL FLOW THROUGH AN AQUITARD

Operating Principle

Often, groundwater movement through aquitards is essentially one-dimensional (vertical flow across an aquitard between adjacent aquifers). In such situations, the average linear velocity and an estimate of the effective porosity provide a simple estimate of travel times through aquitards. The appropriate equation is

$$\bar{v} = \frac{\overline{K_v}}{n_e}\frac{(h_1 - h_2)}{L}$$

where $\bar{v}$ is the average linear velocity through the aquitard, K_v is the vertical hydraulic conductivity, n_e is the effective porosity and h_1 and h_2 represent the hydraulic head at the top and bottom of the aquitard. The travel time through the aquitard is calculated as the aquitard thickness divided by the average linear velocity.

$$t = \frac{L}{\bar{v}}$$

Advantages

This analytical solution is very simple and easy to solve.

Data Expected

The solution provides estimates of vertical flow rates and travel times based on advective flow.

Relevant Hydrogeologic Setting

Applicable where flow through the aquitard can be assumed to be one-dimensional (vertical flow only, little or no horizontal component) and preferential pathways are insignificant.

Limitations

The resulting velocities and/or travel times are only estimates, and as such are only as reliable as the parameters used in the equation. For porous media, the total porosity may provide a reasonable estimate of effective porosity. However, groundwater flow through fractures results in very fast groundwater travel times along the high-conductivity pathways provided by the fracture. The effective porosity of a fracture pathway is very small (yielding a fast velocity and travel time), but it is also difficult to measure; estimates of the effective porosity of fractured deposits typically have large associated uncertainties. Although the groundwater velocity along a fracture can be fast, contaminant transport may be affected by retardation or other transport processes.

This average linear velocity/travel time calculation applies to permeable media, however it does not account for diffusion-dominated transport in non-fractured, low-conductivity materials. In the low-K environments of aquitards, contaminants may migrate via diffusion where the advective flow of groundwater is extremely low.

Cost

Very inexpensive assuming parameter estimates are available.

Companion Tools

These calculations may be a first step in more sophisticated modeling studies.

Site-specific Example

See Chapter 10 for an application of this method to the Nine Springs study site.

ESTIMATES BASED ON NUMERICAL FLOW AND TRANSPORT MODELS

Operating Principle

Numerical groundwater flow and/or transport models solve flow and transport equations for complex situations involving one-, two- or three- dimensional flow, fracture flow, transient flow, advection, dispersion, diffusion, retardation, and chemical reactions. Simple, one-dimensional models may provide useful insight into contaminant transport across an aquitard at a single location. More sophisticated two-and three-dimensional models simulate contaminant concentrations in an aquifer that result from transport across and/or around an adjacent aquitard at site-wide or regional scales.

In some cases, equivalent porous media models (such as MODFLOW (McDonald and Harbough 1988) and MT3DMS (Zheng and Wang 1999)) may be useful to simulate flow and transport through both aquitards and aquifers. These models are calibrated to field measurements of hydraulic head, flow, or chemical parameters. A “dual-porosity” model may be appropriate to simulate contaminant transport in fractured, porous geologic materials. “Dual porosity” refers to the contrasting transport characteristics of the fractures (which allow the flow of contamination with groundwater through the fractures) with that of blocks of low-conductivity material between the fractures (in which transport is dominated by molecular diffusion of the contaminant into the matrix of porous material). These models may be applied to low-conductivity porous media aquitards, as well as aquifers. The *State-of-the-Science* companion report contains a review of dual-porosity and discrete fracture approaches in mathematical models of solute transport.

Advantages

Numerical models can solve complex transport equations and yield continuous solutions over the model domain. They can account for aquitard heterogeneity. Modern modeling codes are computationally efficient and produce high-quality graphic results. Modeling approaches can be selected that are appropriate for various settings and contaminants. For example, a computer code that simulates retardation should be used if the contaminant of interest is likely adsorb to aquitard materials, and models that simulate discrete fracture flow or dual-porosity should be applied where transport across fractured aquitards is considered. Depending on the contaminant of interest, it may be appropriate to assume an aquitard has through-going fractures until field evidence shows otherwise.

Data Expected

Models provide estimates of concentrations, travel times, or breakthrough curves at any point in the model domain.

Relevant Hydrogeologic Setting

Models are useful in all hydrogeologic settings where predictions of concentrations are desired and where adequate field data are available for model construction and calibration. An experienced modeler should select a suitable modeling approach with respect to hydrogeologic setting and the contaminant(s) of concern.

Limitations

Transport models require multiple input parameters, such as source concentrations, dispersivity, porosity, and retardation properties, which are usually poorly known and difficult to measure. Often transport modeling can be expensive and time-consuming. Model results can be difficult to verify and may be highly uncertain in heterogeneous or fractured settings. Depending on the contaminant type and the specific issues of concern, simulating flow and transport through fractured aquitards with an equivalent porous medium model (e.g. MODFLOW, MT3DMS) may not be useful and can be misleading.

Cost

Generally expensive depending on the amount of detail included and the level of sophistication of the simulated processes (on the order of tens to hundreds of thousands of dollars). Requires advanced modeling expertise.

Companion Tools

Transport models are useful after complete site assessment and the construction of a useful flow model. Geochemical and isotopic profile data are useful for model calibration. Models may also be used to optimize additional data collection efforts. For example, where collection of additional field information would serve to reduce uncertainty in model results.

Reference

Zheng and Bennett (2002) provide a comprehensive discussion of transport modeling under assumptions of porous-media flow. Harrison et al. (1992) simulate contaminant migration across a clay aquitard with a sophisticated model of transport through discrete fractures. The *State-of-the-Science* companion report provides additional background on modeling contaminant transport across aquitards.

Example

A transport model developed for the Nine Springs study site is described in Chapter 10.

CHEMICAL ANALYSIS OF CORES

Relevant Hydrogeologic Setting

Cores can be obtained from aquitards in all types of hydrogeologic settings. Analyses can be conducted on samples of the core to determine pore water and other concentrations for natural and anthropogenic chemical constituents. Many different drilling and coring methods are available (Chapter 4); the methods best suited for a particular aquitard depend on the degree of induration and other physical characteristics. The manner and degree to which chemical data from cores contribute to understanding of aquitard integrity differs from one aquitard to the next, depending on the geologic origin of the aquitard and many other factors.

Operating Principle

The primary goal of the core chemical analysis is to determine the concentration distribution of dissolved chemical constituents in the aquitard. This provides insight into the potential for contaminants to migrate through the aquitard. The concentration distributions of natural and anthropogenic constituents, if present, may provide evidence of the processes and pathways governing contaminant transport at a site: diffusion or advection, and the presence or absence of fractures. The natural constituents of most relevance are major ions (e.g., Na^+, Ca^+, Mg^{2+}, $HCO^{3}{}_{-}$., Cl-, $SO^{4}{}_{2-}$), minor constituents (e.g., Br^+, B, F) and isotopes (e.g., O^{18}, ^{2}H,^{3}H, ^{14}C). In some cases, the primary goal is to determine whether the aquitard will emit natural chemical constituents to the aquifer that would cause deterioration in aquifer water quality.

The spatial distribution of natural constituents in aquitards is commonly governed by influences of diffusion and / or advection and, in some cases, geochemical processes operating over geologic time scales. The insights derived from data interpretations in the context of geologic time contribute to the understanding of contaminant transport over the human time scales relevant to water resources management. Some aquitards have been penetrated by anthropogenic constituents (e.g., contaminants, ^{3}H, SF^{6}, CFC's). Determining the distribution of these compounds in aquitards contributes to assessment of aquitard integrity (e.g., Parker et al. 2004).

Pore water for chemical analysis can be obtained from core samples by centrifuge methods, or in the case of unlithified aquitards core samples can be squeezed. For some chemical constituents, such as non-reactive, inorganic species (e.g., chloride, bromide), the core sample can be crushed / disaggregated and then mixed with water to provide a larger volume, dilute water sample for chemical analysis. The original pore water concentrations are calculated using sample weight and porosity relations. For volatile organic contaminants such as chlorinated solvents, complications caused by mass loss due to volatilization cause other approaches to determine concentrations. For example, the core sample can be immersed in methanol or another organic solvent liquid into which the contaminant mass is partitioned (Parker et al. 2004). The chemical analysis is then conducted on the organic liquid containing the mass and then the original pore water concentrations are obtained by calculation (e.g. Parker et al. 2004, Sterling et al. 2005). Figure 9.1 shows a TCE concentration versus depth profile for a clayey glaciolacustrine aquitard in Connecticut. The characteristics of this and other profiles from the site indicate that this aquitard allows contaminant migration governed only by diffusion and therefore the aquitard in the area investigated has excellent integrity.

Advantages

The core analysis method generally provides worthwhile information that cannot be obtained by other methods and, as such, use of this method is generally an essential part of most aquitard integrity investigations. The method provides a means for acquiring profiles of concentration versus depth that have many data points for each core hole. Core analysis generally avoids complications and uncertainties related to analysis of groundwater samples where drilling has induced movement of chemical constituents (e.g., borehole cross connection). The alternative method for obtaining chemical profiles from within an aquitard involves use of nested piezometers or depth-discrete MLSs (Chapter 7). These alternative methods require much more effort to minimize cross connection effects and in some cases such effects are unavoidable.

Data Expected

Chemical analysis of core provides profiles of concentration versus distance along the core for whatever chemical or isotopic constituents are desired. For some constituents, the concentrations represent measurements conducted on actual pore water from the core (e.g., water extracted by centrifuging or squeezing). For other constituents, the concentrations in pore water are calculated from measurements of concentrations in extractants. The number of data points (i.e., number of samples collected from the core) is generally restricted by cost, however the spacing suitable for answering questions relevant to the aquitard under investigation depends on hydrogeologic and other factors.

Limitations

The cost and ease of application of the method varies greatly from aquitard to aquitard. The difficulty of acquiring the constituent concentrations from core differs depending on the chemical constituent and aquitard characteristics. Effective and efficient methodologies have not yet been developed for some constituents.

ENVIRONMENTAL ISOTOPE DISTRIBUTIONS IN GROUNDWATER

Interpretation of environmental isotope distributions can help estimate groundwater age, travel times, potential contamination processes, and aquifer vulnerability. Isotopes can also be used as tracers of water masses flowing from different sources and mixing in different ways. *Isotopes* are atoms of a particular element having slightly different atomic weights due to differences in the number of neutrons in the nucleus. A subset of environmental isotopes are unstable, or radioactive, and decay at different rates into more stable isotopes depending on their *half-life*. If one of the isotopes is unstable, the proportion of that isotope will change over time by *radioactive decay*. If the source or input function of that isotope is known (for example, atmospheric thermonuclear bomb testing was the major global source of tritium), the half-life can be used to estimate how long ago a given water sample entered the groundwater system. Ratios of stable isotopes are indicators of how long water has been in contact with a geologic formation. The longer the residence time, the closer the water isotopic ratio will be to the isotopic ratio of minerals in the bedrock or unlithified material.

The isotopes most often used in aquitard studies are ^{3}H (tritium), ^{2}H (deuterium), and ^{18}O (oxygen-18). For aquitard studies, data are commonly plotted as depth profiles; changes in the profile with depth are interpreted as distance of penetration of different-origin water into the aquitard and can provide a basis for time-of-travel calculations. Many other isotopes (such as carbon, sulfur, strontium, and nitrogen, among others) have proven useful in specific situations (see *Contaminant Transport Through Aquitards: A State-of-the-Science Review*).

TRITIUM

Operating Principle

Tritium (^{3}H), which is radioactive with a decay half-life of 12.4 years, is one of three isotopes of hydrogen in water molecules present in relatively young water. The other two hydrogen isotopes (deuterium ~ ^{2}H and common hydrogen ~ ^{1}H) are stable (i.e. non-radioactive). For groundwater flow systems in granular geologic media (i.e. media where fracture flow is minimal), tritium is used as an indicator of groundwater age, generally providing differentiation of groundwater that entered the groundwater system since the early 1950s from older groundwater (Clark and Fritz 1997) Tritium in precipitation rose markedly in the early 1950s due to atomic weapons testing, which continued until the ban on atmospheric testing in 1963. Since that time, tritium concentrations in the atmosphere have gradually declined but remain above pre-1950's levels. When both tritium and helium-3 concentrations are measured, the age of groundwater in granular media can be determined (i.e. dated) to within a few years or better. In fractured porous media such as fractured clayey or silty aquitards or fractured sedimentary rocks, diffusion into the low-conductivity matrix of the sediments prevents use of tritium or tritium-helium for age dating, but nevertheless these tools can provide valuable insights concerning presence/absence of rapid groundwater flow or solute transport pathways.

In aquitard assessments, the general premise is that groundwater with detectable tritium has traveled wholly or in part along relatively rapid pathways and that groundwater devoid of detectable tritium has traveled along less rapid pathways. Groundwater from within the middle of a relatively thick unfractured clayey or unfractured shale aquitard should have no detectable tritium whereas fracture flow may cause tritium to be present within or throughout an aquitard. If tritium is found in an aquifer above an aquitard and also below the aquitard, the presence of the deeper tritium indicates rapid solute transport pathways through the aquitard or pathways circumventing the aquitard (e.g. aquitard of limited areal extent). Thus, tritium analyses can provide useful insights in various hydrogeologic circumstances. As a general rule, any municipal water supply well that shows detectable tritium should be viewed as a well relatively vulnerable to contamination, regardless of whether or not the aquifer in which the well is positioned is overlain by an extensive aquitard. The detection of tritium in a water supply well presumably protected by an aquitard should prompt assessment of why the tritium is present.

Relevant Hydrogeologic Setting

Tritium can be analyzed for in samples collected from unlithified and lithified aquitards, but the degree of usefulness varies depending on site-specific circumstances.

Advantages

Tritium data can be acquired from any study area where monitoring wells or water supply wells exist. Sample collection is simple and the necessary sample volume is minimal (one L). Several commercial laboratories (the University of Miami Tritium Laboratory, the Environmental Isotope Laboratory at the University of Waterloo, and at CSIRO Isotope Analysis Service, Adelaide, South Australia) conduct the analyses and there is considerable scientific literature available for guidance in the interpretation of tritium results. Tritium data acquired from existing wells in a study area prior to initiation of a drilling program is an inexpensive contribution to develop initial conceptual models of the hydrogeology and the groundwater flow system.

Cost

There are several levels of analysis that differ in precision and detection limit. The cost increases with greater precision and lower detection limit, ranging from $50 to $300 per analysis. The detection limit needed depends on the latitude of the site and site-specific hydrogeologic factors. For example, the level of tritium in precipitation since the early 1950s has been much lower in the southern United States than in the northern States and Canada; in the northern states a higher detection limit might suffice.

Limitations

In some situations, the required 1 L sample volume renders tritium analyses to be unfeasible. For example, if water samples are acquired by crushing or centrifuging core (see previous sections of this chapter), this sample volume may be prohibitive.

Site-specific examples

Isotope profiles through a clayey surficial aquitard in northeastern Wisconsin demonstrate the utility of isotope techniques (Figure 9.2). A series of nested piezometers was installed at depths ranging from 5 to 100 ft below the land surface. Water levels in these piezometers indicate a steep downward hydraulic gradient through the clay. Tritium is detectable in the shallowest piezometers but is not detectable below 15 ft, suggesting that recharge at this site has penetrated less than 15 ft since the cessation of atmospheric nuclear testing in the 1960's. The ^{18}O profile shows a marked shift to more negative values at about 75 ft. Such negative del ^{18}O values are characteristic of precipitation recharged in arctic climates as would have existed in northern Wisconsin at the end of the last glaciation about 10,000 years ago. The implication is that water in the clay below this depth might be very old – possibly of Pleistocene age. Ruland et al. (1991) provide an example of using environmental isotopes to evaluate the role fractures in groundwater flow through a clayey aquitard.

A tritium profile constructed for the Nine Springs field site is presented in a following section on dissolved inorganic species in groundwater.

OXYGEN-18 AND DEUTERIUM

Relevant Hydrogeologic Setting

Oxygen-18 (^{18}O) and deuterium (^{2}H) can be used in all types of hydrogeologic settings, but the degree of usefulness varies greatly from one aquitard study to another depending on site-specific circumstances.

Operating Principle

Like tritium, ^{18}O and ^{2}H exist in water molecules. Their usefulness in groundwater investigations involves identification and tracing of waters with different relative isotopic concentrations. ^{18}O and ^{2}H are stable isotopes most often used to distinguish groundwater source areas or climatic conditions. Surface water bodies tend to be enriched in ^{18}O relative to groundwater because the lighter ^{16}O atoms evaporate more rapidly than heavier ^{18}O atoms. As a result, groundwater that originates as recharge from surface water bodies is commonly enriched in ^{18}O relative to groundwater recharged solely through precipitation. Isotopic fractionation also varies with climate, latitude, and temperature, but the fractionation rates of ^{18}O and deuterium are linearly related. In general, the concentrations of ^{18}O and deuterium in precipitation, and in groundwater recharged through precipitation, plot as a linear relationship called the meteoric water line. Deviations from this line are usually attributed to heavier isotopes being concentrated through evaporation from open water (e.g. lakes and ponds). Groundwater containing a greater percentage of heavier isotopes must have been recharged by surface water.

The most common use of ^{18}O and ^{2}H in aquitard investigations involves comparison of the ^{18}O – ^{2}H signature of porewater from the aquitard to the signature in the groundwater above and below the aquitard. Groundwater with ‘normal’ ^{18}O and ^{2}H have concentrations close to the average of the precipitation in the region. ^{18}O values are close to –9 to -10‰ in the northern central states (e.g. Wisconsin, Michigan, Ohio) and close to –2 to -5‰ in the southern States. Based on the $^{18}O/^{2}H$ ratio, groundwater originating from surface water can be distinguished from groundwater originating from precipitation recharge. This is useful in aquitard investigations if surface waters are the source of groundwater that can be traced down to, or through, aquitards.

Some aquitards have porewaters that originated when the aquitard was formed (for example, when the clay or shale was deposited). This porewater may have the isotopic signature of precipitation during climatic conditions different from present. For example, in the glaciated region of the United States and Canada, nearly all sediments that constitute unlithified aquitards were either deposited by glaciers during the Pleistocene time, or formed by accumulation of sediment in lakes that existed near the end of Pleistocene time. During the Pleistocene, the climate was much colder than at present, and precipitation had a much different ^{18}O – ^{2}H signature. Thick, unlithified aquitards in the glaciated region with very low K and no through-going fractures typically have porewaters with the ^{18}O – ^{2}H signature of Pleistocene-age water. In some circumstances, the absence of such isotopic signatures in an aquitard is evidence that fractures impart a much larger K_{bv} to the aquitard than would otherwise be the case.

Limitations

^{18}O and ^{2}H do not provide a basis for strong interpretations in hydrogeologic settings where groundwater and surface waters have a similar isotopic ratio. For example, if all surface water and groundwater samples from the study area show similar ^{18}O – ^{2}H ratios, the data may not be useful in hypothesis assessment. However, this cannot be determined without first acquiring the information from strategic sampling locations.

Cost

Costs range from about $50 for ^{18}O to about $100 for both ^{18}O and ^{2}H. Laboratories that perform these analyses on a commercial basis include the Environmental Isotopes Laboratory, University of Waterloo, www.science.uwaterloo.ca/research/eilab, and the Stable Isotope Laboratory, University of Ottawa: www.isotopes.science.uottawa.ca .

Site Specific Example

^{18}O and ^{2}H concentrations in springs, lakes, and shallow and deep municipal water supply wells in the Madison area demonstrate the application of this technique in determining sources of water to wells (Figure 9.3). Samples of lake water plot to the right of the meteoric water line, while samples collected from area springs plot to the left of the line. A majority of the samples from the shallow and deep wells plot on or to the left of the meteoric water line, suggesting there is no surface water component in the recharge to these wells. The data indicate that some proportion of surface water flows to the deep well that plots to the right of the line (circled on the graph), suggesting that the well is not fully protected by the Eau Claire aquitard.

The use of ^{18}O as an indicator of very old groundwater at depth in a glacially-deposited clay aquitard is demonstrated in Figure 9.2.

DISSOLVED INORGANIC CHEMICAL SPECIES AND PARAMETERS

Relevant Hydrogeologic Settings

The spatial distribution of dissolved inorganic chemical species (e.g. Cl, SO_4, HCO_3, Na, K, Mg, Ca, NO_3, Br, B, F) and other parameters (e.g. pH, Eh, electrical conductance) may be useful to understanding transport potential across unlithified or lithified aquitards. However the degree of usefulness typically depends strongly on the site-specific circumstances.

Operating Principle

In this investigative method, water samples are obtained from wells above, below, and if possible, within the aquitard, to discern spatial variations that can provide insight concerning aquitard integrity. This investigative method is successful where there are strong contrasts in chemical concentrations between the zone overlying the aquitard, if such a zone exists, and the interior of the aquitard, or between the aquitard interior and the zone immediately below the aquitard. The spatial distribution of each of the inorganic chemical species and the inter-relations between the species may provide insight concerning the groundwater flow paths and/or the dominant processes for solute transport. For example, the spatial distribution of chloride commonly reflects solute transport processes because chloride is conservative; it is not affected by chemical reactions or degradation. If an aquitard has a K_{bv} so low that diffusion is the dominant solute transport process in the aquitard, this can, in some circumstances, be indicated by the chloride distribution (e.g. Desaulniers and Cherry 1989). Analyzing samples from existing wells for these constituents should be considered prior to planning and drilling new boreholes in the study area. All new monitoring wells should be sampled for these constituents.

Advantages

Sampling for dissolved inorganic species and parameters can be easily done when monitoring and/or water supply wells exist in the study area. Useful trends may or may not result from this sampling, but it is relatively inexpensive compared to the cost of drilling. Many commercial laboratories do these analyses using standard methods. In most areas, useful information on the distribution of dissolved inorganic species already exists from previous studies of one type or another. Acquiring additional data of this type results in a more comprehensive and useful data set to assess aquitard integrity. The value of such data is commonly enhanced when other analyses, such as tritium and ^{18}O – ^{2}H, are done on samples from the same wells.

Limitations

In some hydrogeologic circumstances, the spatial distributions of dissolved inorganic species do not provide much value. For example, lack of discernable spatial patterns or complexities cause uncertainty in data interpretation.

Cost

The cost per sample for analyses of a complete suite of major ions and several minor constituents is $100 - $200.

Site Specific Example

Nitrate, chloride and tritium concentration profiles from the Nine Springs field site are shown in Figure 9.4. Samples from the upper aquifer have elevated nitrate and chloride, probably resulting from near-by agricultural practices in the area and the application of road salt. These constituents have not reached the aquitard or deep aquifer at appreciable concentrations at the Nine Springs site.

The tritium data is consistent with the dissolved solute information. A tritium concentration of 9 TUs in the upper aquifer indicates that relatively recent recharge reaches the upper aquifer but does not penetrate the Eau Claire aquitard, where both samples collected were less than the detection limit (<0.8 TU). The Mt Simon aquifer monitoring point contained tritium at a concentration of 1 TU, which we attribute to contamination of the formation water by water introduced during drilling of the borehole.

WATERBORNE VIRUS TESTING

Operating principle

Viruses in groundwater are detected primarily by two methods: 1) Cell culture, in which a water sample is placed over a layer of mammalian cells and any viruses present are visualized by their infection of the cell layer; 2) Polymerase chain reaction (PCR), in which virus nucleic acid (e.g. DNA) is extracted from the water sample and enzymatically amplified to a level where it can be visualized. Viruses that use RNA for their nucleic acid must first be converted to DNA by another enzymatic process called reverse transcription (RT). Integrated cell culture PCR (ICC-PCR) is a combination of the two methods where viruses are first allowed to infect a cell culture and then they are detected in the cells by PCR or RT-PCR. Before virus detection methods are employed, a groundwater sample of about 1000 to 1500 L (250 to 500 gallons) must be concentrated to about 1 L or less using a specialized filter. Common waterborne viruses include enteroviruses, rotavirus, hepatitis A virus, noroviruses, and adenoviruses.

Advantages

Standard water quality indicators, like total coliforms, are not well correlated with virus presence therefore direct detection of pathogenic viruses provides the best assessment of contamination and potential health risk. The cell culture method is the only means of testing for viable infectious virus. The PCR method has a low limit of detection and is extremely specific to the target virus.

Data expected

Cell culture will determine virus presence/absence or quantity, although virus identity must be confirmed by subsequent antibody or PCR-based methods. PCR will indicate virus presence/absence and identify the specific virus type. Virus identity should be confirmed with DNA probes or DNA sequencing. Viruses can be enumerated by real-time fluorescence-based PCR.

Relevant hydrogeologic setting

Groundwater from any type of aquifer or aquitard can be tested for viruses, however the large sample volume required may preclude analysis of waters from low-K environments.

Limitations

Samples should be collected by a trained technician. Virus testing methods are expensive. The large sample volume required may preclude sampling from a small-diameter monitoring well or from a low-conductivity unit. Some viruses cannot be cell cultured (e.g. noroviruses) and some can only be cultured with difficulty (e.g. rotavirus, hepatitis A virus, some adenoviruses). Dissolved substances present in some groundwater can inhibit the PCR method. Without careful technique and proper controls, the PCR method is prone to false positives. The relationship between waterborne virus test results and human health risks has not yet been well defined in the scientific literature, and therefore it is difficult to communicate the implications of detection of viruses in water supplies.

Cost

Costs vary depending on the methods selected (cell culture, PCR, or ICC-PCR), whether travel is involved with sampling, the number and types of viruses tested, the level of enumeration required, and the level of confirmation required for virus identification. Generally, on a per sample basis, cell culture for enteroviruses costs $300 to $500; RT-PCR for five types of viruses and with virus identities confirmed by DNA probes costs between $500 and $1000.

Companion tools

Coliphages are viruses of coliform bacteria and they occur naturally in human feces. Methods for coliphage detection are readily available, easy to perform, and cost on the order of tens of dollars. The relationship between coliphage occurrence and the occurrence of human pathogenic viruses is uncertain. However, a groundwater sample positive for coliphage would suggest that viruses are able to enter the aquifer. A negative coliphage test does not guarantee that human pathogenic viruses are not present.

Site-specific examples

Three municipal water supply wells serving the city of Madison, Wis. were sampled for viruses as a part of this project (Borchardt et al. in review). Two of the wells, numbers 7 and 24, are in highly urbanized areas in the center of the city and are within a few thousand feet of Lakes Mendota or Monona. The third well, number 5, is located on the grounds of the municipal sewage treatment plant, and is within several thousand feet of the Nine Springs field site. Construction records and geologic logs for these three wells report that shale composing the Eau Claire aquitard is present in all three locations. The aquitard is approximately 10 feet thick in wells 5 and 7 and nearly 30 feet thick in well 24. Wells 7 and 24 are cased to depths below the Eau Claire aquitard and presumably draw water from the Mt. Simon aquifer. The casing at well 5 does not reach the depth of the aquitard and groundwater pumped from this well is likely a mix of waters from the Wonewoc and Mt Simon aquifers.

The three wells were each sampled ten times between June 2003 and August 2004. Seven of the 30 samples (23%) were positive for enteroviruses. Other virus groups tested (rotavirus, hepatitis A virus, and noroviruses) were absent in all samples. The enterovirus-positive samples were taken from wells 7 and 24, which are cased though the Eau Claire aquitard. Well 5, which is open to both the upper and lower aquifer, was virus-negative throughout the sampling period. All the enteroviruses were identified with a high level of certainty.

Our conceptual model of contaminant transport across the Eau Claire aquitard leads to several hypotheses regarding the detection of viruses in wells completed in the confined Mt Simon aquifer. Borchardt et al. (in review) present several hypotheses for virus transport to these deep wells. The most likely pathway is transport down the annulus of the well itself, through deteriorated or poorly-installed grout. Flow along this pathway would produce rapid downward movement of water with delivery directly to the well bore. Although the three wells tested in this study were drilled, cased, and grouted according to accepted practice it is nearly impossible to confirm that the grout has remained intact over the entire length of the casing in wells that are now 30 or 40 years old.

ASSESSMENT OF DNAPL PATHWAYS

Relevant Hydrogeologic Settings

DNAPL may flow through unlithified or lithified aquitards if preferential pathways exist. Fractures pose the most likely DNAPL pathway. The appropriate initial strategy in aquitard investigations is to assume that fractures exist in the aquitard until such time as data acquired indicates their absence. This strategy is appropriate if there is reason to believe that DNAPLs have been used, stored or disposed of in the area overlying the aquitard.

Operating Principle

The assessment of the presence of pathways that could allow DNAPL flow through an aquitard does not involve a particular method, but rather it involves application of a group of specific methods described elsewhere in this report. Aquitards devoid of preferred pathways for DNAPL flow are those in which the flow of all fluids is intergranular (sometimes referred to as porous media flow) and there are no preferential pathways such as fractures, root holes, and *multi-aquifer wells* and boreholes. Aquitards allowing only intergranular flow are typically incapable of allowing DNAPL penetration. However, aquitards with through-going open fractures may allow DNAPL flow through the aquitard into the underlying aquifer, if the fracture apertures are large enough to permit DNAPL entry and flow. Therefore, DNAPL pathways assessment should involve acquisition of various types of data sets to assess the presence or absence of open, through-going fractures. Generally, the most important types of data relate to:

1. determining the geologic origin and post-depositional history of the aquitard
2. hydraulic head measurements in space and time under natural and pumping conditions
3. spatial distributions of stable isotopes (e.g. ^{18}O, ^{2}H)
4. radioactive isotopes (e.g. ^{3}H, ^{14}C)
5. major ions and other natural inorganic species
6. if contaminants exist in the aquifer or zone above the aquitard, analyses of contaminant concentration in aquitard core
7. drilling of angled boreholes to evaluate presence of vertical fractures

It is not possible to prove with complete certainty that through-going fractures capable of DNAPL transmission are not present in an aquitard, because such fractures may have small apertures and they may be widely spaced. However, use of several of the investigative methods listed above can result in sufficiently reliable conclusions for decision-making by water managers. Not all of these methods need to be used at all sites. In some cases, only one or two methods provide sufficient information to conclude that through-going open fractures likely capable of DNAPL transmission are present. In other cases, a few but not necessarily all of the methods will be adequate to conclude that DNAPL pathways are unlikely.

Advantages

In areas where DNAPLs are known or suspected contaminants, application of a formal, multi-faceted strategy to determine the likelihood of DNAPL pathways results in greater reliability of conclusions concerning DNAPL migration to an aquifer or well.

Data Expected

The type and number of methods applied and the intensity of the investigation should depend strongly on the site-specific conditions. In some cases, only one or two methods are needed; at other sites, the use of all methods may be appropriate.

Limitations

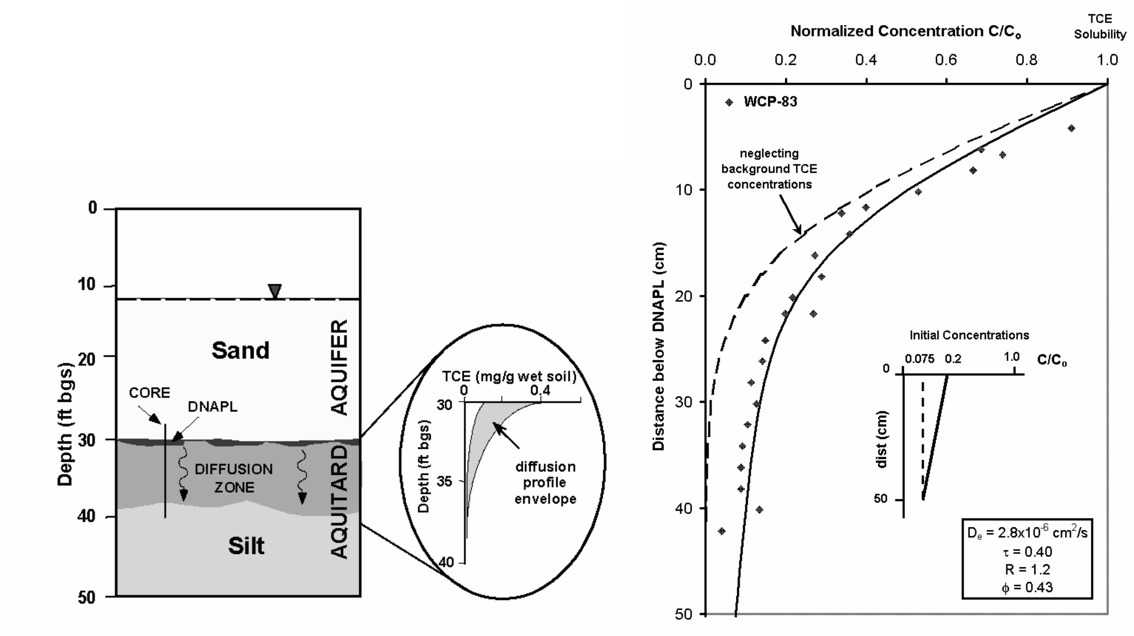
Even after intense field investigation, considerable uncertainty may remain concerning aquitard integrity with respect to DNAPL.

Cost

The cost of determining aquitard integrity with respect to DNAPLs can be small if data collected early in the study indicate the presence of transmissive fractures. The cost may be very large if no fractures become evident and there is a desire to establish the lack of fractures with a high degree of certainty.

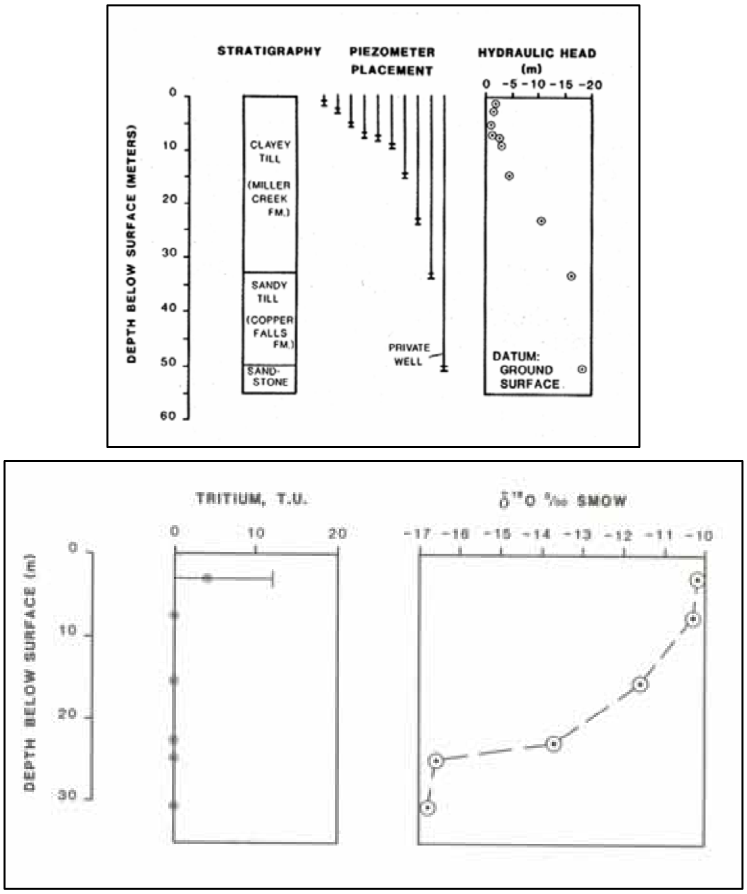
Site Specific Example

Parker et al. (2004) describe an aquitard study in Connecticut where DNAPL lying on top of an unlithified clayey aquitard was found to have no pathways into the aquitard.



Source: Parker et al. 2004. Reprinted from *Journal of Contaminant Hydrology.* Vol. 74, Parker, B. L., J. A. Cherry, and S. Chapman. Field Study of TCE Diffusion Profiles Below DNAPL to Access Aquitard Integrity. pp. 197-230. Copyright 2004, with permission from Elsevier.

Figure 9.1 Profile of conditions causing TCE contamination in an aquitard and results of 1D simulations of the 12-month TCE diffusion cylinder profiles.



Source: Bradbury et al. 1985

Figure 9.2 Profiles of hydraulic head, tritium, and oxygen-18 in a clayey surficial aquitard in northwestern Wisconsin. Top: piezometer depths and hydraulic head. Bottom: isotope concentrations.

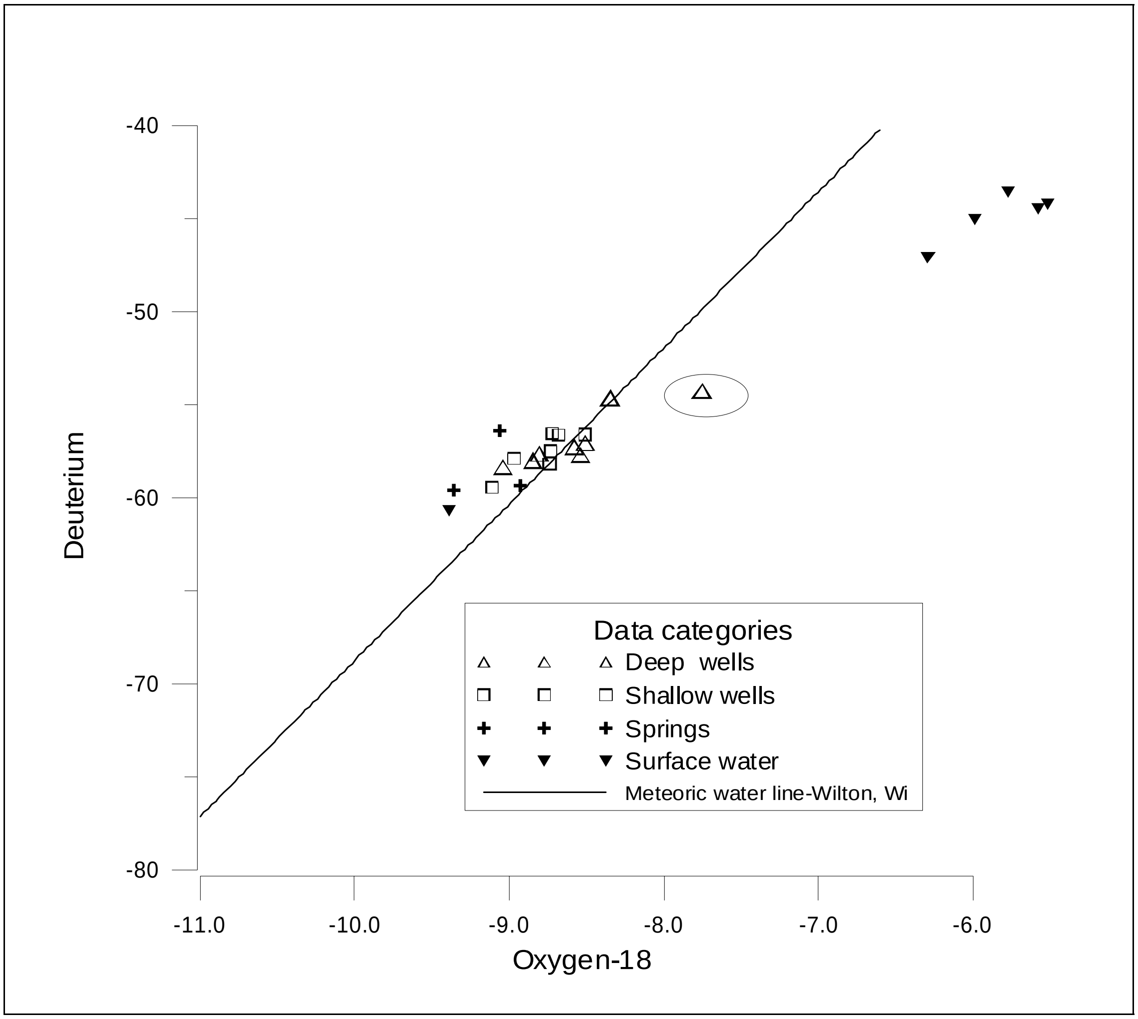


Figure 9.3 Oxygen-18 and deuterium concentrations in Madison-area lakes, springs and groundwater wells. One of the deep wells (circled) plots to the right of the meteoric water line, suggesting it has some component of surface water.

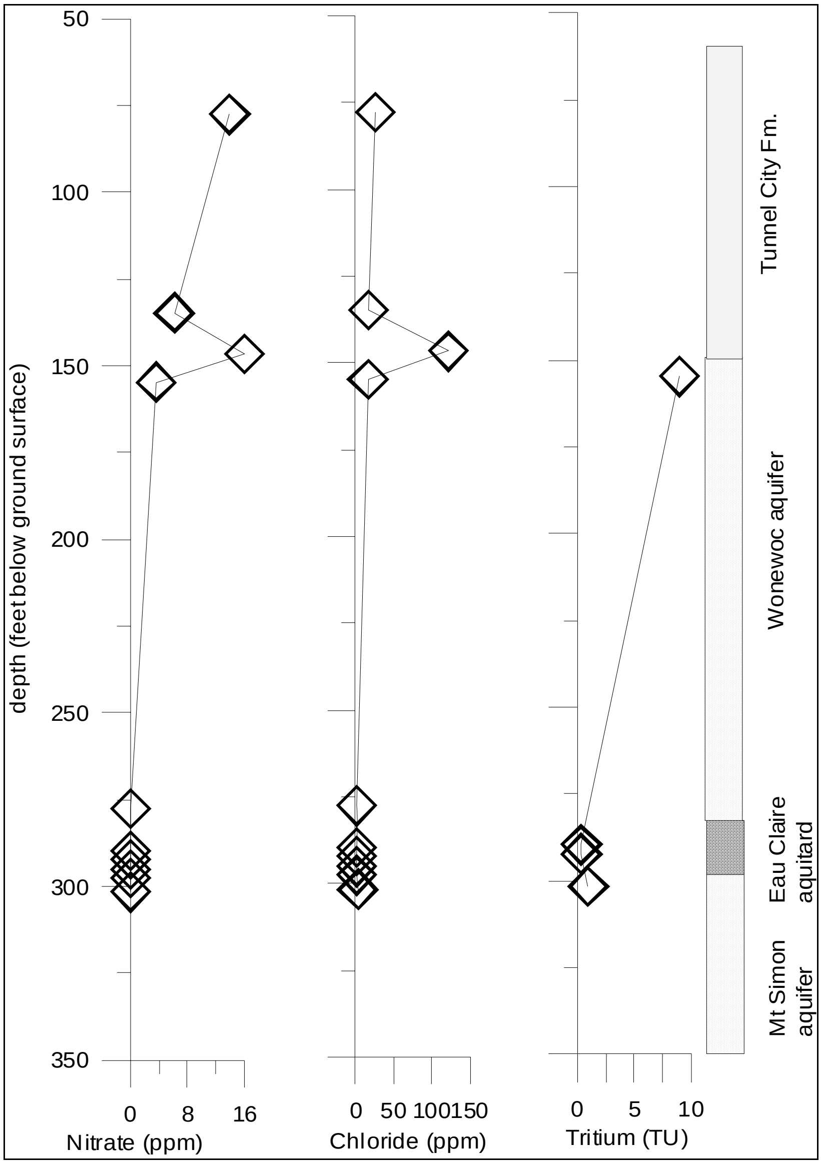


Figure 9.4 Nitrate, chloride and tritium concentrations at the Nine Springs site.

CHAPTER 10
INTEGRATING INFORMATION AT REGIONAL AND SITE SCALES – A FRAMEWORK FOR UTILITY MANAGERS

The bulk of this document describes a series of techniques for obtaining data about aquitards at field sites. Each technique – core analysis, hydraulic tests, geophysical logging, etc.- provides a single type of data, usually limited to a single site or borehole. Yet the water utility or water manager is usually more concerned about aquitards at some larger scale – the scale of a well field, municipality, or contamination site. From the standpoint of aquifer protection, aquitards may provide barriers to contamination of adjacent aquifers. Consequently, understanding the spatial extent and continuity of an aquitard, and its hydraulic relationships to adjacent units, can be critically important, yet the extrapolation of point data over large areas is often problematic, and acquiring the appropriate data can be time-consuming and expensive.

Integrating and synthesizing multiple sets of information into a coherent framework is a challenging yet essential part of aquitard analysis. Water managers seek an appropriate framework for decision making in the context of specific questions to be answered, and these questions need to be posed in terms of the conceptual model. Such questions can range from simple to complex, and the solution methods also range from simple to complex. For example, the question *"how rapidly can groundwater move through this aquitard?"* might be addressed by a simple analytical calculation. Questions such as "*what is the distribution of contamination in this aquitard?"* or, *"is this well susceptible to contamination from that source?"* might require extensive analysis using a numerical solute transport model.

A STEPWISE APPROACH TO AQUITARD EVALUATION

Evaluation Protocol

The following protocol for aquitard studies moves from relatively simple and inexpensive mapping activities to sophisticated data collection and analyses. We recommend that most aquitard studies follow a similar stepwise procedure to maximize resources and save time and money. The investigative process should continue only as far as necessary to achieve the desired goal. For example, studies of regional aquifer vulnerability might be complete after steps 1 through 3, while studies involving contaminant remediation at specific sites will require the extensive data gathering and analyses of steps 4 through 11.

1. Collect existing data (previous studies, maps, well logs, geologic information, etc). Develop a conceptual model of the aquitard geology. Define the geologic units composing the aquitard. Construct preliminary maps of aquitard extent and thickness, and determine whether aquitards are present in the area of interest.
2. Combine the geologic conceptual model with available hydraulic data (water table and potentiometric maps) to form a conceptual model of the groundwater flow system, including all significant hydrogeologic units. Evaluate the regional and local importance of the aquitard and its probable role in the groundwater flow system.
3. Construct a conceptual model of contaminant transport pathways across the aquitard of interest, for particular contaminants of concern. Make preliminary estimates of groundwater velocity and travel times using simple analytical equations. Refine estimates

for particular contaminants of concern, based on appropriate retardation, diffusion and decay parameters.

4. Where existing wells are available and where these wells are known to draw groundwater from a single hydrogeologic unit (e.g. not a well that is open across multiple aquifers and aquitard(s)), sample for isotopes and/or solutes to evaluate transport across aquitard of interest.
5. Plan site investigations: assess the importance of determining the presence or absence of preferential contaminant transport pathways, such as fractures, through the aquitard. Select methods appropriate to the hydrogeologic setting.
6. Conduct appropriate site investigations: install boreholes, obtain rock core, conduct geophysical investigations, and install multilevel monitoring equipment.
7. Prepare detailed data analysis based on new field data, including stratigraphic correlations, aquitard thickness analyses, estimations of aquitard hydraulic properties.
8. Collect and analyze water and core samples from the aquitard for chemical, isotopic, and biologic constituents of interest.
9. Construct and calibrate numerical groundwater flow models at appropriate scales to address the problems at hand. The model(s) may include aquifers as well as the aquitard of interest, to yield insight into flow across a region. Models constructed to evaluate a particular well or contamination site may be more limited in scope.
10. Construct numerical fate and transport models that include transport and attenuation processes (e.g. retardation, dilution, decay) appropriate to contaminants of concern, and appropriate to the hydrogeologic setting (e.g. porous medium or fracture flow).
11. Use the models to simulate future conditions, processes, or impacts; draw conclusions and refine conceptual models.

We recommend the stepwise use of analytical and numerical groundwater flow and solute transport models as tools for data evaluation in most aquitard studies. These models provide a means to integrate aquitard information within the context of groundwater flow systems and spatial heterogeneity, and provide a basis for extrapolation of conclusions from site-specific field measurements to larger areas. Groundwater flow and solute transport models can range from simple to complex. Simple analytical calculations, such as velocity calculations based on Darcy's Law, yield first-approximation estimates of flow and transport of dissolved contaminants through aquitards. In many cases, much more sophisticated approaches are warranted, including simulations of dissolved contaminant transport with influences of diffusion, sorption and degradation through fractured materials. The current state of the science does not provide for simulations of virus or DNAPL migration through fractured aquitards.

Modern groundwater modeling codes such as MODFLOW (McDonald and Harbaugh 1988), MODFLOW2000 (Harbaugh et al. 2000), CRAFLUSH (Sudicky and Frind 1982), and FRACTRAN (Sudicky and McLaren 1992), when combined with graphical interfaces such as Groundwater Vistas (ESI 2004), are powerful and flexible tools that have become a standard part of hydrogeologic practice. When constructed properly, groundwater models can and should integrate all aspects of the hydrogeologic data collected, and as such the model can serve as a database and as a simulation tool.

For aquitards, the use of numerical models of groundwater flow has the following advantages over analytic models:

1. The true extent and thickness of the aquitard can be simulated, including known pinch-outs, windows, and facies changes. Vertical heterogeneity can be simulated using several model layers to represent a single aquitard.
2. The models can reproduce the hydraulic head distributions in aquifers adjacent to the aquitard (below and above the aquitard in the case of buried aquitards; below the aquitard in the case of surficial aquitards). Failure to reproduce the known head distribution can point to data inconsistencies such as unrecognized windows or breaches in the aquitard.
3. The models can reproduce the hydraulic head distribution *within* the aquitard. Correct simulation of hydraulic gradients means the role of the aquitard in the dynamics of the overall groundwater flow system is understood, and transport across the aquitard may be simulated.

The following example applies some of these analysis techniques to studying the Eau Claire aquitard.

Example: Groundwater flow and transport through the Eau Claire aquitard

Regional Vulnerability Analysis

In Dane County, Wis., the Eau Claire aquitard lies between two bedrock aquitards and controls groundwater movement from one aquifer to another (see Appendix A for bedrock stratigraphy). The Eau Claire is important for protecting many of the municipal wells in the county from contamination. Most of these wells are completed in the lower sandstone aquifer (the Mt Simon aquifer). The following discussion demonstrates the overlaying of geometric and hydraulic data for estimating the vulnerability to contamination of municipal wells in Dane County (Figure 10.1).

Effect of Shale Presence and Thickness

One simple method for a preliminary assessment of the vulnerability of the municipal wells is to overlay the wells on a map of aquitard thickness. Figure 10.2 shows the distribution of the Eau Claire aquitard across Dane County. Its thickness ranges from absent (in the NE part of the county) to over 20 ft thick (in the NW part of the county). Comparing the distribution of wells to the distribution of the aquitard it is clear that some wells (those in the NE part of the county) are probably much more vulnerable to contamination from the surface than wells in the western parts of the county where the aquitard is thicker. In the central part of the county the aquitard thins over an ancient lake basin, and wells there might be quite vulnerable. It is important to understand, however, that the thickness map itself provides only a preliminary and relative comparison of well vulnerability because it ignores the physical properties of the aquitard and, most importantly, ignores the driving head on the groundwater flow system.

Effect of Hydraulic Gradients

In order for most dissolved contaminants (dense contaminants such as DNAPLs are an exception) to move advectively in groundwater from the upper to the lower aquifer there must be a vertical hydraulic gradient downward. Figure 10.3 shows areas of downward groundwater flow in Dane County; these are areas where the hydraulic heads in the upper sandstone aquifer are higher than the head in the lower sandstone aquifer. The figure shows how major surface water features influence the head distribution. In the humid Midwest, lakes and rivers are often groundwater discharge points, and groundwater moves upward beneath them. However, drawdown caused by pumping wells can reverse hydraulic gradients even near large surface water bodies; such reversals have occurred in central Dane County over parts of the large lake basins.

Joint Effect of Gradients and Aquitard Thickness

Overlaying the effects of thickness and gradient gives an improved estimate of aquifer vulnerability. Figure 10.4 shows the results of a groundwater flow model in which mathematical particles were introduced at the bottom of the upper aquifer and tracked until they reached the top of the lower aquifer. The resulting travel time represents vertical travel through the aquitard due to advection, and takes into account both regional hydraulic gradients and aquitard thickness. In the shaded part of the map the simulated advective travel time through the aquitard is less than 10 years. In these areas, which cover much of the county, even deeply cased wells are vulnerable to contamination. However, it is interesting to note that in some places where the aquitard is thin or absent (SE part of county) the travel time is very large because hydraulic gradients are small. Conversely, in places where the aquitard is relatively thick (west-central Dane County) there is still potential for relatively rapid downward movement. It is important to stress that this analysis depends on the parameters input to the flow model (such as K and effective porosity) that are difficult to estimate. The accuracy of these results also depends on the quality of the model construction and calibration.

Site-Specific Velocity Calculation

Simple calculations allow estimation of groundwater flow rates and travel times through the Eau Claire aquitard adjacent to active water-supply wells at the Nine Springs site in Madison, Wis.. Field data collected at this site consist of hydraulic head profiles including measurements from above, below and within the aquitard, formation thicknesses, and analyses of K_h from slug tests conducted with short-interval packers. Flow through the aquitard is assumed to be predominately vertical; lateral groundwater movement in the aquitard is insignificant.

Calculation of Effective Vertical Hydraulic Conductivity

Field investigations have shown that the Eau Claire aquitard at Nine Springs consists of two distinct units – an upper shaley sandstone 16 feet thick and a lower gray shale 5 feet thick. For the purposes of a simple Darcy analysis we can lump these units together to form one aquitard having a thickness of 21 feet. Based on model calibration, the K_v of these two units are, respectively, 0.00067 ft/day and 0.0001 ft/day.

For one-dimensional groundwater flow through a layered system, the K_{bv} of the layered system is given by the following equation (McWhorter and Sunada 1977):

$$\overline{K_{bv}} = \frac{\sum_{i=1}^{n} L_i}{\sum_{i=1}^{n} \frac{L_i}{K_{iv}}}$$

where

$\overline{K}_{bv}$= bulk vertical hydraulic conductivity
L_i = thickness of individual bed i
K_{iv} = vertical hydraulic conductivity of individual bed I
n = number of layers

For the Nine Springs example, the equation becomes

$$\overline{K_{bv}} = \frac{16+5}{\left(\frac{16}{0.00067}\right)+\left(\frac{5}{0.0001}\right)} = 0.00028 \text{ ft/day}$$

Calculation of Average Linear Velocity

The average linear velocity through the aquitard is expressed as

$$\bar{v} = \frac{\overline{K_{bv}}}{n_e}\frac{(h_i - h_2)}{L}$$

where $\bar{v}$ is the average linear velocity, n_e is the effective porosity and h_1 and h_2 represent the hydraulic head at the top and bottom of the aquitard.

For the Nine Springs site, this equation is solved as

$$\bar{v} = \frac{0.00028}{.05}\frac{(840-805)}{21} = 0.0093 \text{ ft/day, or } 3.4 \text{ ft/yr}$$

The travel time through the aquitard is calculated as the shale thickness divided by the average linear velocity.

$$t = \frac{L}{\bar{v}}$$

For Nine Springs, the travel time is then

$$t = \frac{21 ft}{3.4\, ft/yr} = 6.2 \text{ years}$$

Based on these calculations, a conservative solute (i.e. undergoes no retardation or decay) beginning at the top of the Eau Claire aquitard could move by advection vertically through the aquitard and reach the underlying aquifer in 6.2 years. It is important to understand that this travel time is an estimate based on parameters that are uncertain. For example, the travel time is inversely proportional to effective porosity, n_e. Effective porosity is difficult to measure and might range from as low as 0.01 to as high as 0.3. Accordingly, the travel time estimates have equal uncertainty unless constrained by other data such as geochemistry, isotopes, or tracer experiments. In this example, the travel times associated with a range in n_e from 0.01 to 0.3 is 1.3 to 37 years.

Solute Transport Simulation

A simple 1-dimensional numerical solute transport simulation that includes the effect of dispersion provides an improved estimate of travel times through an aquitard. The objective of this simulation is to demonstrate the effect of *hydrodynamic dispersion* on transport through the aquitard under realistic hydraulic gradients. In the formulation of the model, hydrodynamic dispersion includes the effects of dispersion due to mixing caused by variations in K plus mixing caused by molecular diffusion. In this case, where the simulation represents transport through a low-K_v aquitard, the *hydrodynamic dispersion* term is dominated by diffusion.

The simulations represent the movement of a dissolved solute from the base of the Wonewoc aquifer overlying the Eau Claire aquitard, through the Eau Claire, to the top of the underlying Mt Simon aquifer. Using data from the Nine Springs research site, we constructed a one-dimensional solute transport model using the MT3DMS transport code of Zheng and Wang (1999). The conceptual model is a vertical column through the Eau Claire aquitard (Figure 10.5) with groundwater flow moving downward under the hydraulic gradient measured at the site. The model assumes that flow is through an equivalent porous medium; any effect of fractures in the aquitard are ignored. The effect of dispersion (represented by the longitudinal dispersivity term) will be small because it is dominated by diffusion through the low-K aquitard. The model is steady state, with boundary conditions of constant head at the base of the Wonewoc Fm (top of the column) and the top of the Mt Simon Fm (bottom of the column). The value of 0.01 ft used for longitudinal dispersivity is based on the review compiled by Gelhar et al. (1992).

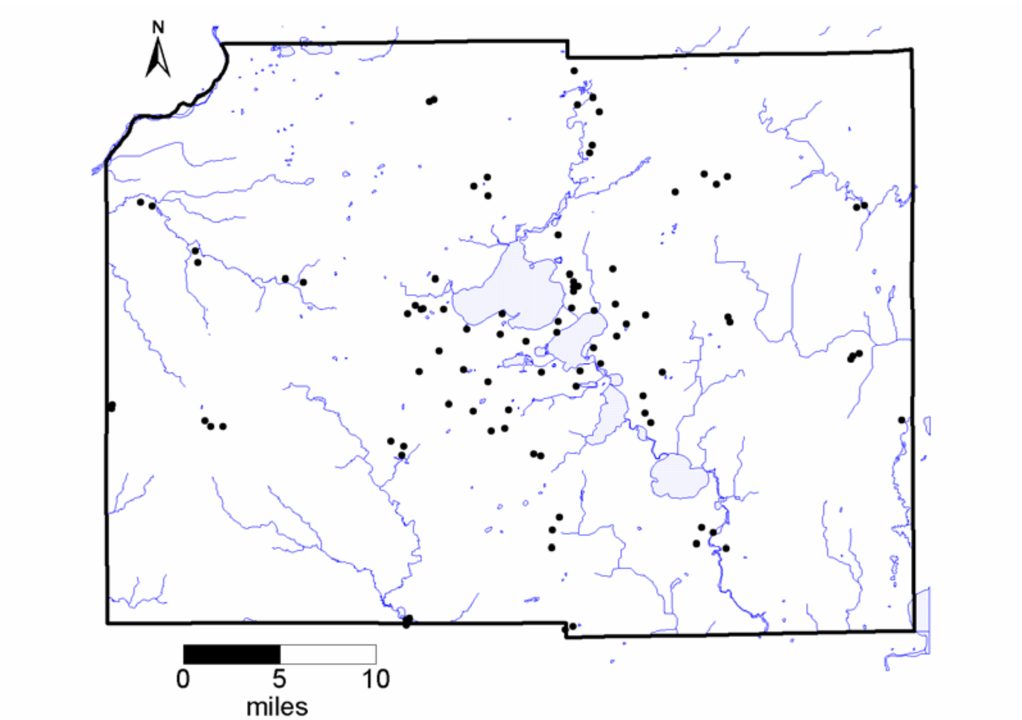
The numerical model to solve this problem consists of 23 rows, 3 columns, and 1 layer. The model parameters used in the simulations are as follows:

Cell width along rows = 1 ft
Cell width along columns = 1 ft
Layer thickness = 1 ft
Constant head (top of model) = 840 ft
Constant head (base of model) = 805 ft
Porosity = 0.05
K_v = 0.00067 ft/day (upper sandstone/shale); 0.0001 ft/day (lower shale)
Longitudinal dispersivity = 0.01 ft
Simulation time = 5 years (1825 days)
No sorption or degradation
Initial concentration = 1.0 at top of column; continuous source

The hydraulic head distribution was solved using MODFLOW, followed by transport simulations using MT3DMS. In two subsequent model runs, longitudinal dispersivity was increased to 1.0 ft and decreased to 0, to demonstrate the effect of this parameter on the results.

The simulations show that a dissolved substance is transported to significant depths within the Eau Claire aquitard in a reasonably short time period (on the order of 5 years). Figure 10.5 shows concentration profiles predicted by the model at a simulation time of 5 years. Figure 10.6 shows simulated concentrations versus time at the base of the section. Results are expressed as normalized concentrations (C/C_0) for a conservative contaminant. The simulation with no dispersion shows that without dispersion the contaminant would move as a continuous front to a depth of 17 ft in 5 years, but would not reach the underlying aquifer, in agreement with the previous analytical calculation of 6.2 years to reach the lower aquifer. Using a dispersivity appropriate for this shale facies, 0.01 ft, the contaminant reaches a depth of 19 ft at about 5% of the initial concentration. Increasing the dispersivity to a value of 1, which is more appropriate to simulating transport through higher-K materials, leads to breakthrough of a concentration of 30% of the source in 5 years.

It is important to emphasize that these simulations demonstrate only the breakthrough concentrations at the top of the underlying aquifer. They do not indicate the concentrations of the contaminant in the aquifer once the contaminant has mixed with ambient water in the aquifer. Based on the relative volumes of water moving vertically through the aquitard and moving horizontally through the underlying aquifer, dilution would result in much lower overall contaminant concentrations in the underlying aquifer. The effect of dilution could be simulated with a three-dimensional flow and transport model.



Source: Adapted from Krohelski et al. 2000

Figure 10.1. Dane County, WI, showing major surface water features. Dark dots represent the locations of municipal wells.

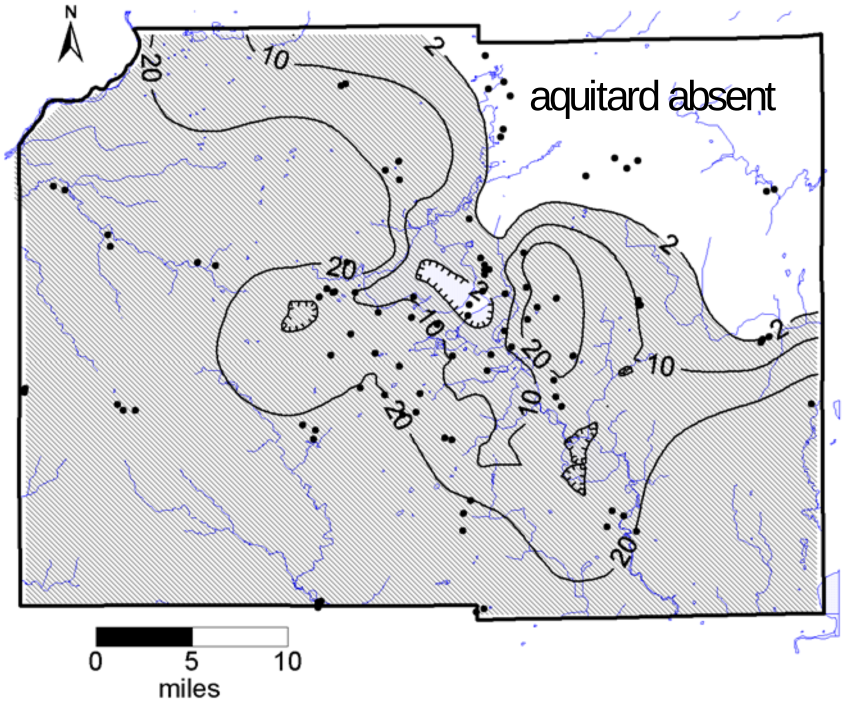


Figure 10.2. Approximate thickness of the Eau Claire aquitard in Dane County. Shaded areas show aquitard presence. Thicknesses in feet.

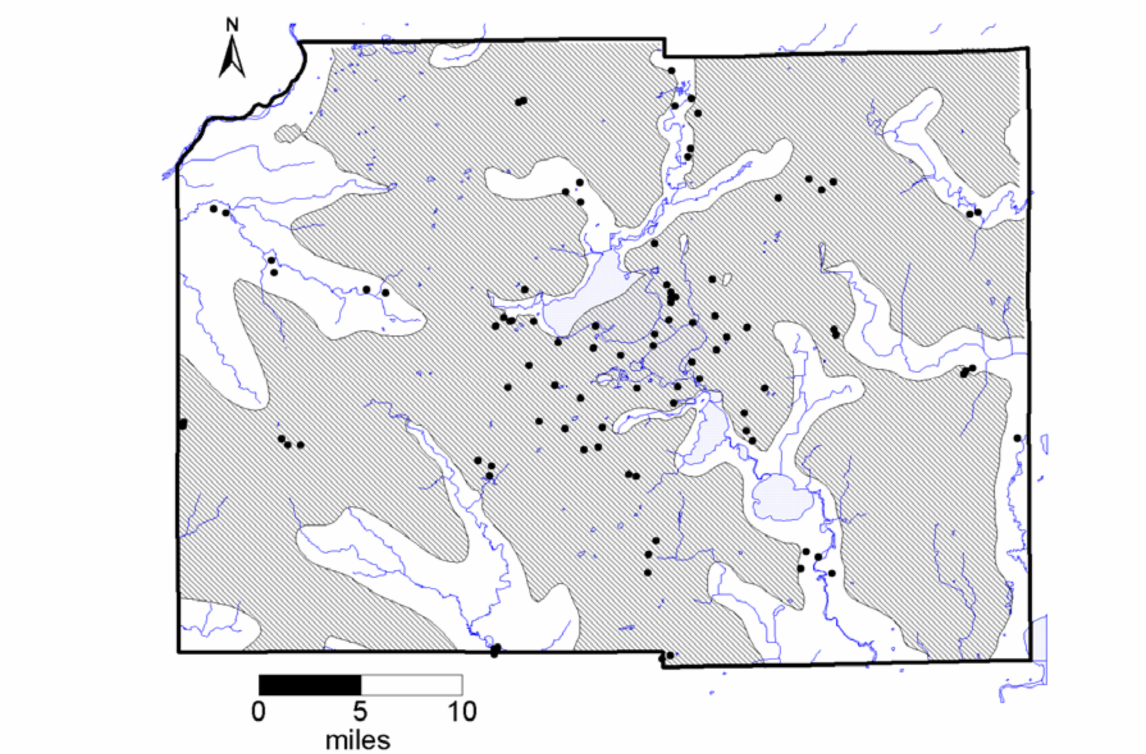


Figure 10.3 Downward flow in Dane County. In shaded areas there is a downward hydraulic gradient from the upper to the lower aquifer.

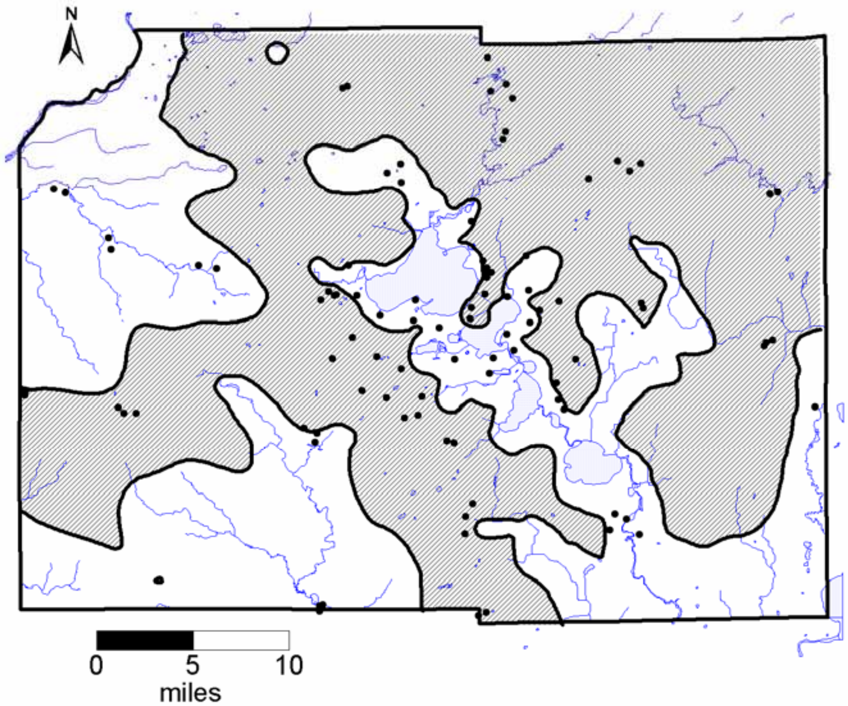


Figure 10.4. Probable areas of rapid movement between the upper and lower aquifers. In the shaded area the simulated travel time from the upper to the lower aquifer is less than ten years. Results from a numerical groundwater flow model of Dane County.

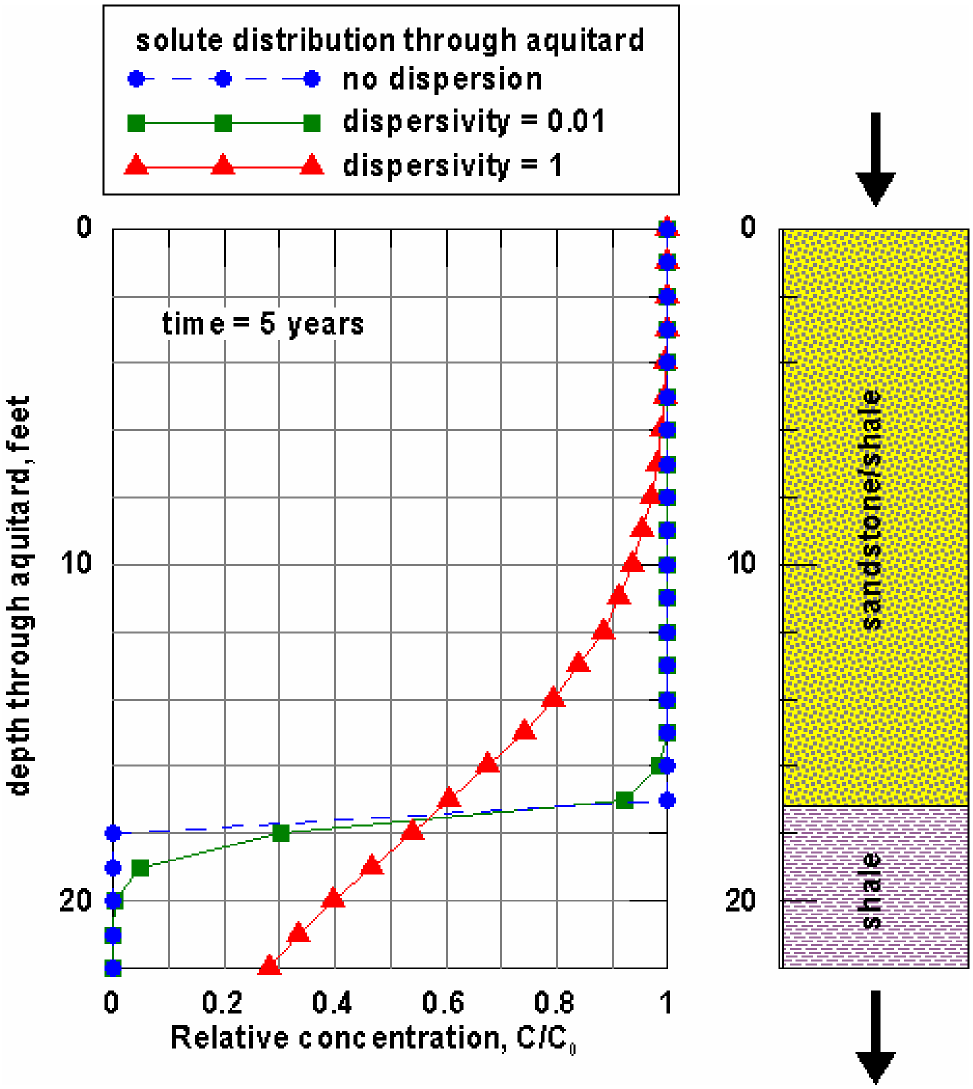


Figure 10.5 Results of contaminant transport through aquitard at 5 years.

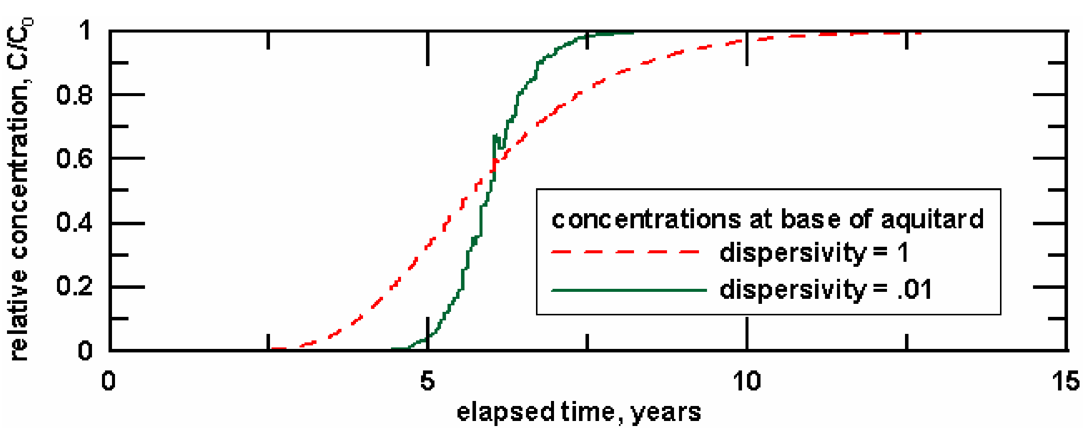


Figure 10.6 Simulated concentration over time at the base of the aquitard.

APPENDIX A
THE NINE SPRINGS AQUITARD STUDY SITE

BACKGROUND

Field investigations of a bedrock aquitard at a research site near Madison, Wis. were an important part of this AwwaRF-funded aquitard project. The field investigations demonstrate and test various techniques of aquitard study, and results of the field investigations are used as examples throughout this technical guidance document. This Appendix documents activities at the field site.

SITE SELECTION

The Nine Springs study site is located on the southeast side of the city of Madison, in Dane County, south-central Wisconsin (Figure A.1). Groundwater is the sole source of municipal water supply in Madison, and the site is located within several hundred feet of two municipal wells operated by the Madison Water Utility. Nearby property owned by the Madison Metropolitan Sewerage District provided a suitable location for field investigations and the installation of testing equipment. The Nine Springs site is well suited as a demonstration site because an important regional subsurface aquitard, referred to as the Eau Claire aquitard, occurs at the site and throughout south-central Wisconsin (Figure A2). Bradbury et al. (1999) and Krohelski et al. (2000) discuss the Eau Claire and its function in the regional groundwater flow system in Dane County. The Eau Claire aquitard ranges in thickness from zero to over 60 feet in Dane County, and separates the lower Mt Simon aquifer from an upper aquifer. Most municipal groundwater production in Dane County is from the Mt Simon aquifer. Consequently the Eau Claire aquitard is critical for protecting the Mt Simon from contamination, and knowledge of the extent, thickness, and characteristics of the Eau Claire is important for siting new wells, for assessing the potential for contamination of existing wells, for wellhead protection studies, and for regional groundwater flow modeling.

GEOLOGY AND HYDROGEOLOGY

The Eau Claire aquitard is an informally-named part of the Cambrian Eau Claire Formation, and occurs about 280 feet below the surface at the Nine Springs site. Figure A.3 shows a cross section through two municipal wells and one test well drilled for this project. The Eau Claire aquitard lies between sandstones of the Wonewoc and Mt Simon Formations. The Eau Claire at this location consists of clayey to sandy siltstone with thin laminae of fine-grained siltstone and shale units probably deposited in a low-energy offshore environment.

The Nine Springs site is within a major cone of depression caused by groundwater withdrawals from wells in the Madison Metropolitan area (Bradbury et al. 1999). The water table at the site lies in near the top of bedrock, about 30 feet below the land surface. The potentiometric surface of the Mt Simon aquifer (the level that water would rise to in cased wells completed in the Mt Simon) lies about 30 feet below the water table as a consequence of the regional pumping. As a result there is a steep downward hydraulic gradient from the water table to the Mt Simon aquifer, and the direction of vertical groundwater flow is downward.

The two municipal wells near the site, wells 5 and 30, are completed differently. Well 5 is an older well with a casing terminating above the Eau Claire aquitard. Well 5 is currently on line pumping about 1200 GPM, and draws water from both the Mt Simon aquifer and the overlying Wonewoc sandstone. Well 30 is a newly-completed well that is cased through the Eau Claire aquitard. Well 30 draws water only from the Mt Simon aquifer, but was not online at the time of this study (2003 – 2004).

FIELD METHODS

The objective of field activities at the Nine Springs site was to investigate the Eau Claire aquitard in detail by obtaining samples of the aquitard, measuring its physical and hydraulic properties, and testing water quality. The investigation included drilling, geophysical logging, packer testing, installation of several types of multilevel sampling equipment, and monitoring hydraulic head and water quality.

Drilling

The Nine Springs drilling program was designed to maximize resources by installing a relatively inexpensive air-rotary well through the entire section and then using this well to identify critical stratigraphic intervals for subsequent diamond-bit coring. Three boreholes were installed at the Nine Springs site during 2003. The first hole, NS-1, was installed using air-rotary drilling to a depth of 310 ft, about 10 ft below the base of the Eau Claire shale interval. This 6-inch diameter hole was cased to a depth of 42 ft. WGNHS geologists collected drill cuttings at 5-ft intervals during drilling and constructed a preliminary geologic log based on the cuttings. A suite of borehole geophysical logs, including a video log, from this borehole helped target the depths of interest for acquisition of core.

Following analysis of the drill cuttings and geophysical information from NS-1, we installed two additional boreholes. For each of these holes, an air-rotary drill rig was used to bore and case an open hole to the top of the desired core depth. Coring then proceeded using an NQ diamond core bit and wireline system. This produced a nominal 3-inch diameter hole and 1.75-in diameter core.

Geophysical Logging

Geophysical logging at the Nine Springs site included a complete suite of logs: natural gamma, normal resistivity, spontaneous potential, caliper, temperature, fluid conductivity, and borehole flowmeter (both spinner and heat-pulse). In addition, we collected borehole images using Mount Sopris OBI-40 and ABI-40 optical and acoustic imaging tools. These logs produced a very detailed profile of the site, with emphasis on the properties of the Eau Claire aquitard. Figure A.4 is a composite log showing major geophysical logs for the site.

Packer Testing

A series of 45 short-interval straddle-packer tests were conducted in wells NS-2 and NS-3 to measure the hydraulic head distribution along the open boreholes and estimate K_h of the formation materials. The packer string consisted of two commercially available 3-inch diameter packers suspended from a cable and inflated with nitrogen. The straddle distance was 2.2 feet. The straddled interval was connected to the surface using 1.5-in ID flexible plastic tubing. For each test the packers were moved to the desired interval and inflated. The water level change in the packed zone was monitored with a pressure transducer and data logger. Once the packed head stabilized, the head was displaced using either a volume of distilled water (for low-conductivity zones) or compressed air (for high conductivity zones). The water level recovery was measured using a data logger. Recovery times ranged from a few seconds for high-K zones to over one day for low-K zones.

Installation of Multilevel Monitoring Systems

All three holes at the Nine Springs site were completed with MLSs. The 6-inch hole (NS-1) was instrumented with a series of buried pressure transducers sealed in place with bentonite backfill (Chapter 7). The two cored holes (NS-2, open to the Tunnel City and upper Wonewoc Formations, and NS-3, open to the Eau Claire Formation and the top of the Mt Simon) were instrumented with FLUTe™ flexible liner systems and pressure transducers (Chapter 7). The side-by-side instrumentation allowed direct comparison of the hydraulic data collected by the two different instrumentation methods. Both systems were connected to recording data loggers powered by solar cells for continuous data collection. Figure A5 shows examples of hydraulic data collected with these systems. Results of groundwater sampling from the site are presented in Chapter 9.

RESULTS AND CONCLUSIONS FROM THE NINE SPRINGS SITE

Work at the Nine Springs research site and in other areas of Dane County during the course of this project led to significant changes in our conceptual models of the geology and groundwater flow system, and most significantly, in our assumptions about the protection afforded by the Eau Claire aquitard to wells completed in the Mt Simon aquifer. The use of coring techniques during drilling provided high-quality, intact samples of the Eau Claire, so that we understand the formation to include intervals of varying thicknesses of shaley sandstone and shale across the county. This variation results from changes in the sedimentary depositional environment across the region in the geologic past. The practical implications of this are:

1. Our regional-scale map of aquitard thickness based primarily on geologic logs that describe drill cuttings (Figure 10.2) is reasonable.
2. The aquitard consists of two hydrofacies: an upper, more conductive, and thicker unit of interbedded sandstone and shale, and a lower, less conductive and thinner shale facies.
3. Determining the site-specific thickness and head profile of the aquitard should be a priority at any site where there is contamination in the overlying aquifer that is a potential threat to water quality in the deep system.

We used three methods to collect vertical profiles of hydraulic head within the aquitard. Data from these systems are in good agreement (Figure A.5) and show very large downward vertical gradients in the aquitard: 0.3 across the upper hydrofacies and 6 across the lower hydrofacies. The practical implications of these findings are:

1. The two hydrofacies that constitute the Eau Claire aquitard have differing hydraulic properties—the lower facies holds up the majority of the head differential between the Wonewoc and Mt Simon aquifers.
2. Pumping for municipal supply from the Mt. Simon aquifer induces extreme downward gradients across the Eau Claire. This gradient is a strong force, resulting in relatively fast advective travel times across the aquitard even though portions of the aquitard have a very low K_v.
3. Any strategies that will reduce the drawdown in the deep aquifer (such as reducing pumping rates or optimizing well locations and pumping schedules) will reduce the vertical gradient across the aquitard and increase the protection afforded by the aquitard.

We sampled monitoring wells and municipal wells for indicators of groundwater age and quality, and for viruses. At the Nine Springs site, anthropogenic constituents have penetrated into the upper aquifer but have not reached the depth of the Eau Claire aquitard. Viruses were detected in samples from two of the three municipal wells tested during this project. These two wells are cased below the Eau Claire aquitard. Based on these lines of evidence, we reached the following conclusions:

1. Where preferential pathways are not present, the thickness of the upper aquifer permits dilution of dissolved constituents to the extent that the deep aquifer may be well-protected from these contaminants.
2. Preferential pathways through the aquitard, such as erosional windows in the lake basins or imperfections in the grout and casings of individual wells, leave many deeply-cased wells vulnerable to contamination from constituents that are of concern at very low concentrations, such as viruses.

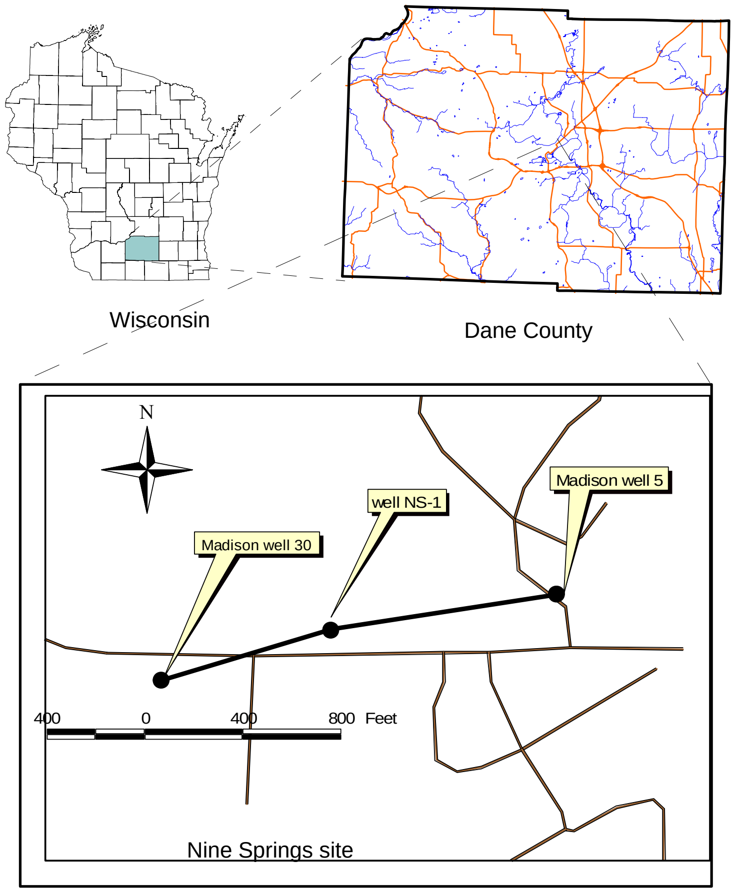
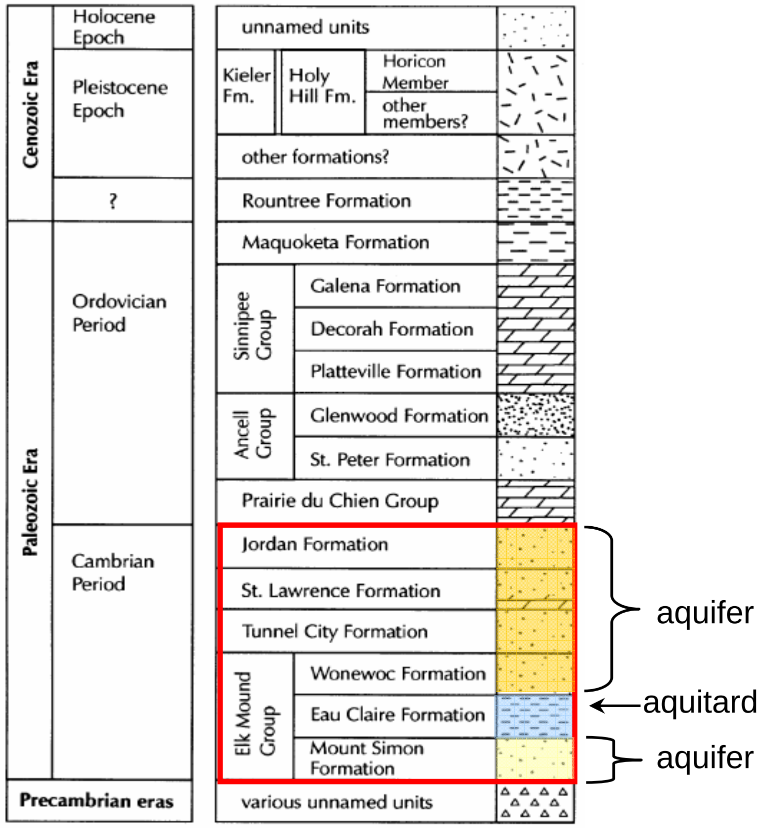


Figure A.1 Location of Nine Springs aquitard study site.



Source: Bradbury et al. 1999

Figure A.2 Stratigraphic section for south-central Wisconsin.

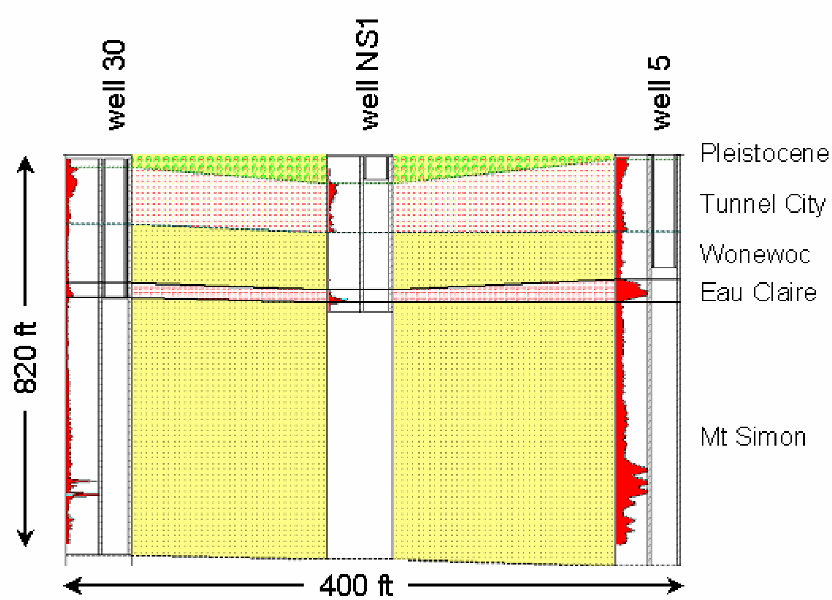


Figure A.3 Cross section across Nine Springs site. For each well the natural gamma log and casing depth are shown. The gamma signal recorded at well 30 is dampened relative to the logs from NS-1 and well 5 due to the large diameter of well 30 (30 inches). See Figure A.1 for section location.

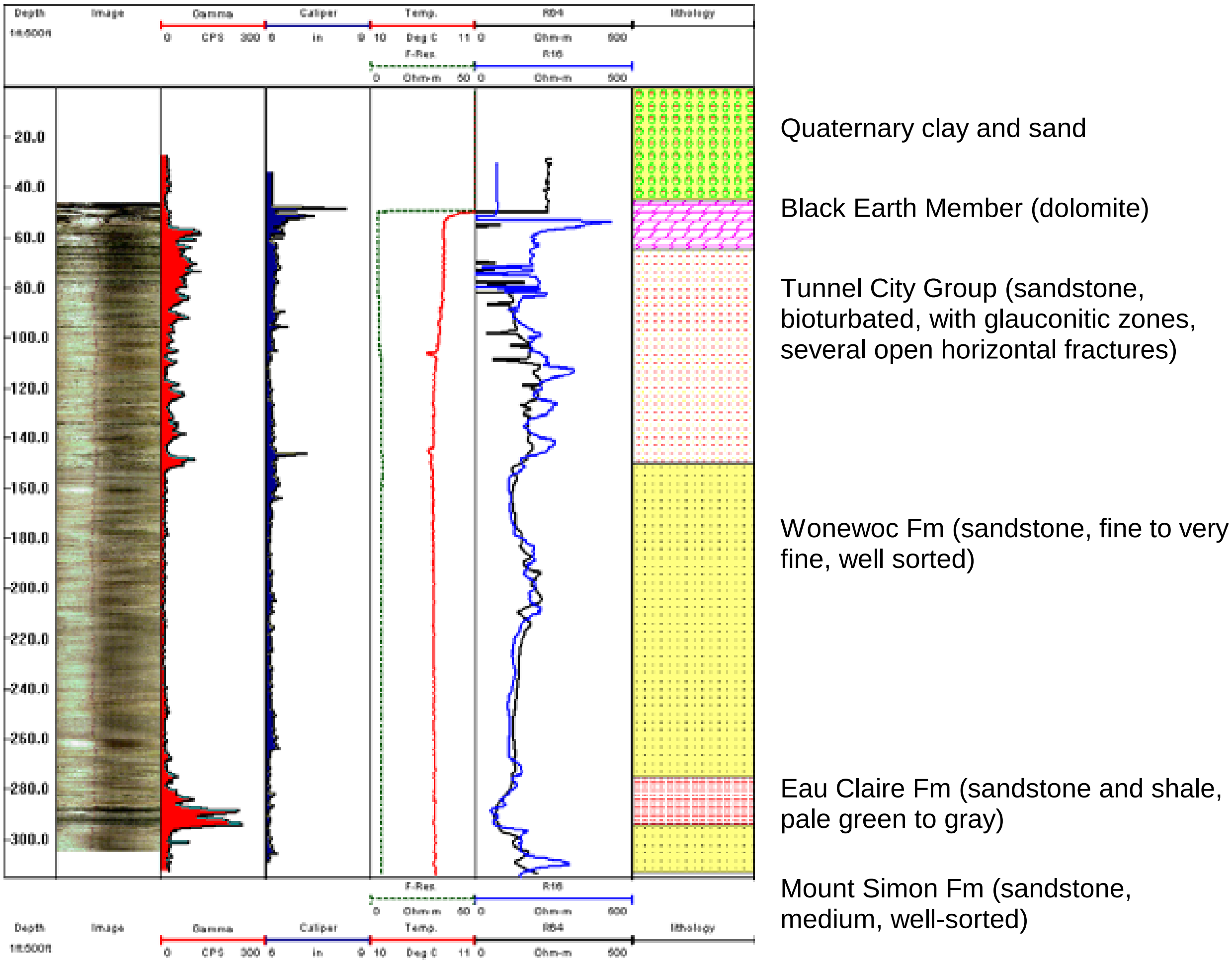


Figure A.4. Composite geophysical and lithologic logs of well NS-1 at the Nine Springs aquitard site.

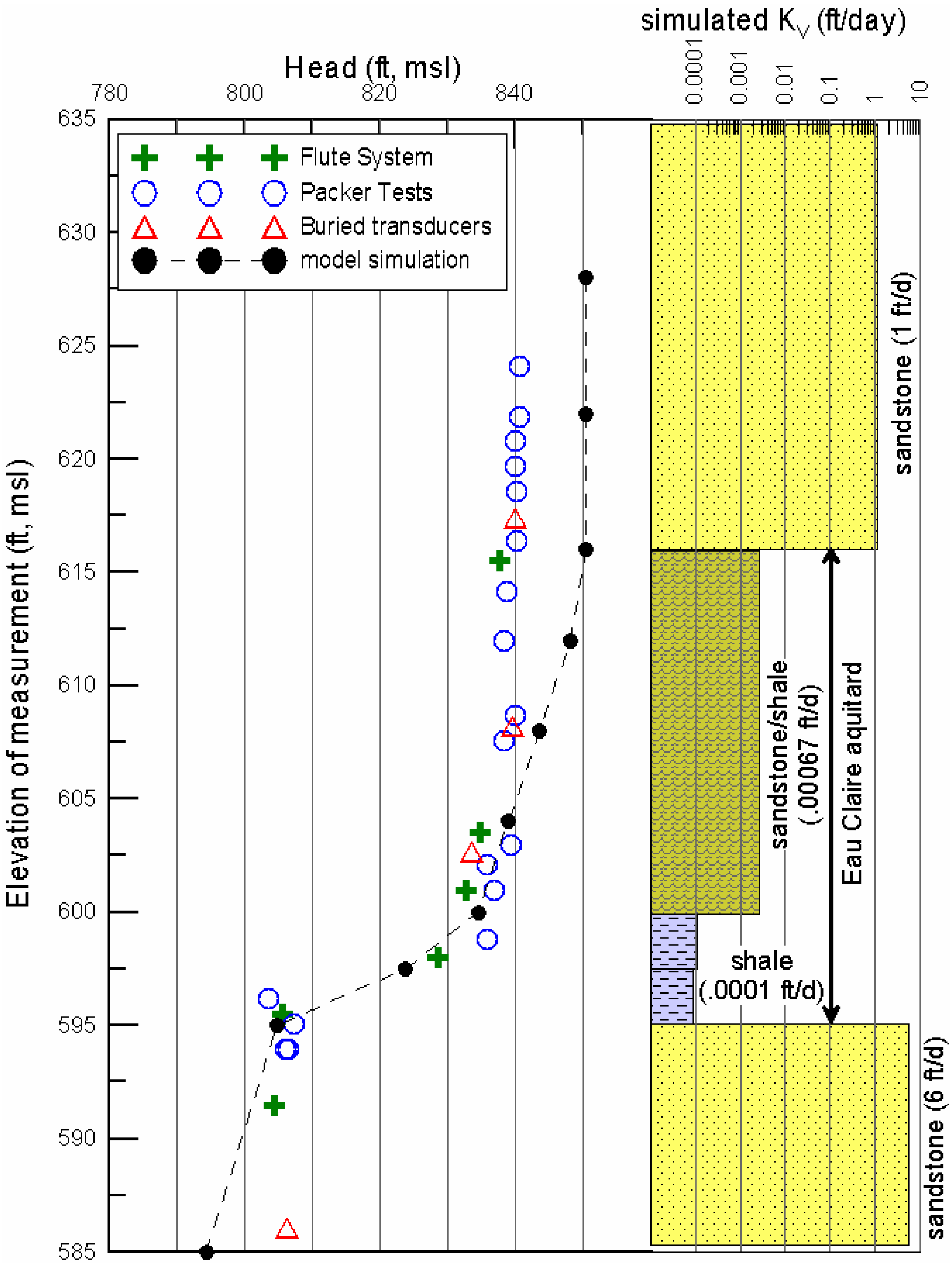


Figure A.5. Summary of hydrostratigraphy, hydraulic conductivity estimates, and hydraulic head measurements at the Nine Springs site.

APPENDIX B
CONCEPTUAL MODELS: EAU CLAIRE AQUITARD

Geologic Conceptual Model

A conceptual model of the geologic setting includes a discussion of the conditions that existed in the geologic past that result in the current assemblage of particular sediments and rock layers. The purpose in compiling this description of the geologic depositional origins of the Eau Claire aquitard is to reduce the uncertainty associated with our interpretation of sparse data of uncertain quality. In other words, we would like to apply a common sense check on our map of aquitard thickness and extent (Figure 3.1), and so we pose the question: Is the map of the extent and thickness of the aquitard, and the presence or absence of windows in the aquitard, a reasonable interpretation based on our understanding of the regional geologic setting?

The variability in the natural system at different spatial scales makes map construction (Figure 3.1) difficult. In Dane County, there is clearly a trend of aquitard thinning from west to east across the county (Figures 3.1 and 3.8), but there are also areas within the county where the thickness of the shale varies dramatically over very short distances. For example, along the western shore of one of the central lakes, the thickness of the shale recorded in geologic logs from two wells that are 375 feet apart differs from 10 to 35 feet. These wells are so close together that they plot on top of each other in Figure 3.1.

The geologic conceptual model yields insight into local conditions but cannot typically be used to predict the location of particular features. For example, the conceptual model may include a description of interbedded sandstone and shale. However, the conceptual model will not yield a prediction of the thickness of the shale beds at a particular location. The following interpretation of regional variations in the Eau Claire Formation was prepared by Dr. David LePain, a sedimentary geologist at the Wisconsin Geological and Natural History Survey:

The Eau Claire Formation is marked by extreme lithologic variability throughout its distribution in Wisconsin (Thwaites 1923). The formation was named for exposures of fossiliferous shale, siltstone, and sandstone in the city of Eau Claire, in west-central Wisconsin, where it consists of approximately 100 feet of interbedded shale, siltstone, and fine-grained sandstone. In northern Sauk County (immediately west of Dane County) the Eau Claire Formation is devoid of shale, and siltstone is present only as relatively thin laminae between thicker sandstone beds (Clayton and Attig 1990). South of the Baraboo Range, in southeastern Sauk County, the Eau Claire Formation once again includes an appreciable thickness of shale and siltstone (Clayton and Attig 1990).

The Eau Claire Formation thins dramatically from southeastern Sauk County to the vicinity of Madison in central Dane County, where a "shale facies" has been recognized on gamma ray logs (Figure 3.8). At the Nine Springs field site, the Eau Claire Formation is 25 feet thick, yet includes a shale-rich succession over 10 feet thick that is unlike anything observed in outcrop. Here, the shale facies includes a relatively thick genuine shale. In Cottage Grove, east of the Nine Springs site, shale is present only as thin laminae (less than a few tenths of an inch thick) that drape thicker sandstone beds, and the most conspicuous drapes are limited to the lower 20 feet of the interval identified on gamma ray logs as the shale facies (Figure 3.8). Based on lithologies observed in core, the Eau Claire Formation is absent at Cottage Grove, and sandstones of the Wonewoc Formation rest directly on similar appearing sandstones of the Mt. Simon Formation. The shale facies recognized on the gamma ray logs from Cottage Grove are likely the result of the thin shale drapes and, possibly, the presence of detrital potassium feldspar in the finer-grained sandstones.

These regional variations in the thickness and lithologic character of the Eau Claire Formation can be explained by proximity of the depositional site to a north-south-trending increase in the elevation of the Precambrian rock referred to as the Wisconsin arch. The Wisconsin arch extends southward from northern Wisconsin, through the eastern part of Sauk County, and continues southeastward through the central part of Dane County (Thwaites 1940, his Figure 1). At locations far from the influence of the Wisconsin arch, the Eau Claire Formation is thick and records deposition in shallow marine environments. At locations near the crest of the Wisconsin arch, the Eau Claire is thin and locally absent. Where present near the crest of the arch, the Eau Claire Formation records deposition in shallow-marine environments very close to the paleo shoreline.

Flow System Conceptual Model

Our conceptual model of the groundwater flow system in Dane County includes aquitards and aquifers (Figure B.1). Recharge occurs in areas of higher topography and follows local flowpaths through the upper bedrock and sand and gravel aquifers. Discharge from these local flowpaths feeds creeks and streams, while some flowpaths through the shallow system recharge the deep bedrock aquifer (the Mt Simon aquifer). The recharge to the Mt Simon occurs through windows in the Eau Claire aquitard (for example, under Lake Mendota) and through downward groundwater flow across the aquitard. The conceptual model presented by Bradbury et al. (1999) and Krohelski et al. (2000) can be updated and refined with data presented in this report: the variation in thickness of the shale facies of the Eau Claire, and revised estimates of hydraulic conductivity and hydraulic head within and across the aquitard.

Conceptual Model of Contaminant Transport Across the Eau Claire Aquitard

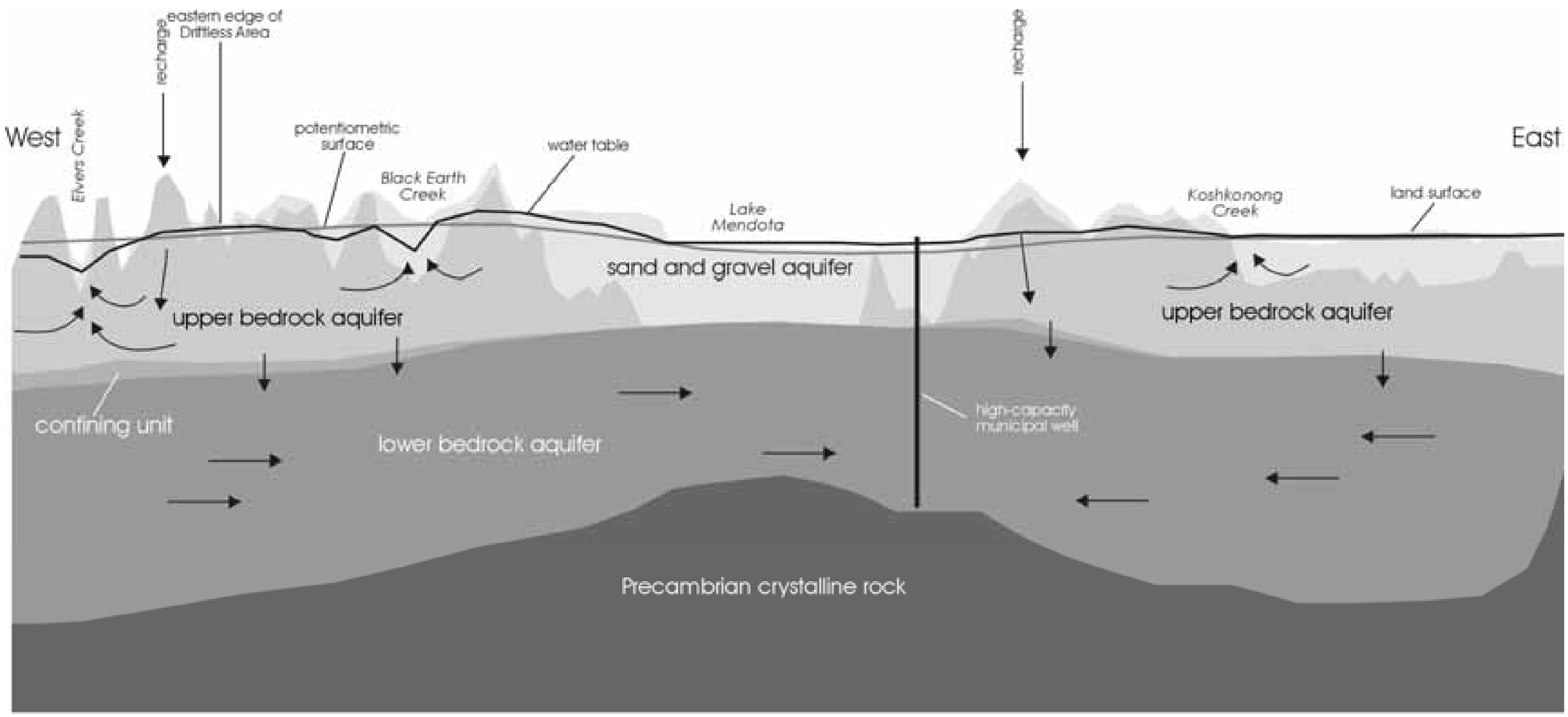
Our conceptual model of contaminant transport across the aquitard involves four potential pathways.

1. Through-going fractures or multi-aquifer wells can provide pathways for particulates (viruses or microbes) and DNAPL. This transport pathway is not critical in considering transport of dissolved constituents because the volume of water transported is likely relatively low. While we are uncertain about the presence of through-going fractures, multi-aquifer wells are documented in well construction records.
2. Breaches in the integrity of municipal well casing, either through the grout or a breach in the metal casing, also provide a pathway for DNAPL and particulates. This is a likely route of transport for the virus detections in samples collected from municipal wells (Chapter 9).
3. Geologic windows in the aquitard are a pathway for shallow groundwater of poor quality to recharge wells in the deep aquifer. This is a pathway of concern for non-point sources of dissolved constituents (such as nitrate from agricultural land use surrounding Madison) and point sources (such as local plumes of dissolved constituents of gasoline and chlorinated solvents that are ubiquitous in the greater Madison urban and suburban

areas). There are at least two significant types of geologic windows in the Eau Claire aquitard: the lake basins where the Eau Claire shale facies was likely eroded, and around the edges of the areal extent of the aquitard. Dilution caused by mixing with ambient water quality in the deep aquifer may partially mitigate the effect of dissolved contaminants transported from these geologic windows.

4. The fourth route of transport is advective flux and diffusion across the aquitard. This is a potential pathway for aqueous, or dissolved, constituents. Travel times across the aquitard along this pathway are shortened by the large, downward vertical gradient across the aquitard induced by pumping from the deep aquifer. The degree to which this pathway threatens the water quality of the deep system is tempered by the thickness of the upper bedrock aquifer. Dilution and dispersion along the predominantly lateral flow paths in the upper aquifer lead to very low concentrations of contaminants at the top of the aquitard.

This conceptual model of transport across the aquitard suggests that each municipal well completed below the Eau Claire has a unique susceptibility to contamination. Although broad, the conceptual model is useful because it can be applied to a particular well based on the well's location in the flow field and known or suspected sources of contamination. Based on information about the Eau Claire compiled in this report, estimates of travel times to a particular well could be calculated for a specific contaminant type and a specific source area.



Source: Krohelski et al. 2000

Figure B.1 Conceptual model of the groundwater flow system in Dane County, Wis. The confining unit is the Eau Claire aquitard, the upper bedrock aquifer is generally the Tunnel City and Wonewoc Formations, and the lower bedrock aquifer is generally the Mt Simon Fm.

GLOSSARY

Aquifer: a layer of geologic deposits that is sufficiently permeable to supply economically useful amounts of water to wells.

Aquitard: a layer of low-conductivity geologic deposits that contains water but does not yield economically useful amounts of water to wells. An aquitard generally restricts the flow of groundwater to adjacent high-conductivity formations.

Groundwater flow system: the series of aquifers and aquitards, topography, groundwater recharge and discharge areas found within a hydrogeologic basin. The boundaries of a regional groundwater flow system are the regional groundwater divides.

Cone of Depression: a depression in the water table that forms around a pumping well.

Colloid: a particle less than 1 μm in diameter. Colloids may be mobile or immobile in groundwater flow systems, depending upon the size of the colloid relative to the size of pores in aquifer and aquitard materials.

Conceptual model: an understanding of the groundwater flow system that can be tested, refined and updated with new information. The conceptual model may include a written description and /or a series of drawings, typically describing aquifers, aquitards, flowpaths, and areas of groundwater recharge and discharge.

Degradation: chemical transformations due to biological, chemical or radioactive processes that reduce the overall contaminant mass in the flow system. In some cases, a contaminant may degrade to a product that is also a contaminant, such as when trichloroethylene transforms to cis, 1,1 dichloroethylene or vinyl chloride.

Dilution: reduction in contaminant concentration due to mixing with less- or non-contaminated waters. The processes of dispersion (mixing due to changes in groundwater velocity) and molecular diffusion (spreading along a concentration gradient) contribute to dilution.

Flow path: the path traced out by a given particle of water as it flows from one point in the *flow system* to another.

Flux: rate of flow or velocity through a porous medium, may be expressed in units of length per time (e.g. feet/day); or as a volumetric flow rate, in units of volume per time (e.g. gallons per minute). In either case this refers to an overall rate of groundwater flow, such as the rate of aquifer recharge or rate of withdrawal from a well, rather than the velocity of an individual particle of water through an aquifer.

Fractures: a crack or fissure in the subsurface. Depending on its aperture or width, the fracture can provide a pathway for rapid transport of groundwater and contaminants.

Delta (δ) Notation: a standard comparison of the isotopic ratio, $^{18}O/^{16}O$ and $^{2}H/^{1}H$, of a sample to the standard mean ocean water (SMOW) expressed as per mille (parts per thousand):

$$\delta^{18}O = \{(^{18}O/^{16}O)sample \div {}^{18}O/^{16}O)SMOW) - 1\} \times 1000$$
$$\delta^{2}H = \{(^{2}H/^{1}H)sample \div (^{2}H/^{1}H)SMOW) - 1\} \times 1000$$

Groundwater flow: the movement of water through pores in sediment and rock; is governed by Darcy's Law: Q=KIA, where Q is the volumetric discharge, K is the hydraulic conductivity, I is the hydraulic gradient, and A is the cross sectional area perpendicular to flow.

Half-life: the time ($t_{1/2}$) required to reduce the number of parent atoms by one-half, through the process of radioactive decay.

Homogeneous: a property that is uniform in space. For example, a homogenous sand deposit has similar grain size, packing, porosity and hydraulic conductivity everywhere within the deposit.

Hydraulic conductivity (K): A measure of how easily water moves through a permeable medium. The horizontal hydraulic conductivity (K_h) is a measure of how easily water can move in the horizontal direction and the vertical hydraulic conductivity (K_v) is a measure of how easily water can move in the vertical direction. Due to the stratified nature of geologic materials, the horizontal hydraulic conductivity is typically higher than the vertical hydraulic conductivity by one or more orders of magnitude.

Hydraulic cross connection: head variations within an open borehole result in a gradient within the open borehole under static, or non-pumping , conditions. This leads to flow of groundwater through the borehole, into the borehole from fractures or zones of higher hydraulic head and out from the borehole through fractures or zones of lower hydraulic head.

Hydraulic head: the total pressure at a point within the groundwater system. In general, head is the same as the elevation of the water level in a piezometer or the elevation of the water table in an unconfined aquifer.

Isotope: isotopes of a particular element have the same atomic number but different atomic weights due to a different number of neutrons in the nucleus.

Karst: areas where the bedrock, usually limestone or dolomite, has been dissolved by surface water or groundwater. Karst landscapes may have deep bedrock fractures, caves, disappearing streams, springs, or sinkholes. These features can be isolated or occur in clusters, and may be open, covered, buried, or partially filled with soil, vegetation, water or other miscellaneous debris.

Lithified: sediments that form rock due to induration or hardening by cementation, pressure or heat

Lithology: the rock types, such as sandstone, shale or siltstone, present in a stratigraphic unit

Macropores: large openings in the shallow subsurface, typically formed by tree roots or burrowing animals.

Multi aquifer wells: wells that are constructed with an open, un-cased borehole across an aquitard into an underlying aquifer. Multi-aquifer wells provide a pathway for flow and transport across an aquitard into an aquifer due to *hydraulic cross connection*.

Nuclide: An atom of a particular element with a given number of neutrons, which defines the isotope of that element.

Numerical model: A computer program is used to approximate the solution to a set of governing equations, boundary conditions and initial conditions that describe a groundwater flow system. MODFLOW is one of the more widely-used groundwater flow models.

Particle Tracking: A modeling procedure that traces out flow paths, or pathlines, by tracking the movement of mathematical particles placed in the modeled groundwater flow field.

Permeability: A measure of how easily a fluid moves through a medium. The permeability of a material is a similar concept to its hydraulic conductivity. Permeability is independent of the fluid, whereas hydraulic conductivity is a measure of a material's permeability to water.

Porosity (Total): The ratio of the volume of void spaces in a rock or sediment to the total volume of the rock or sediment.

Porosity (Effective): The ratio of the volume of void spaces through which water or other fluids can travel in a rock or sediment to the total volume of the rock or sediment. The effective porosity is typically less than the total porosity because many void spaces in a rock or sediment are either not interconnected or are too small to allow fluids to pass through.

Radioactive decay: The process by which unstable or radioactive nuclides spontaneously disintegrate over time with a certain probability, according to their half-life.

Retard or retardation: The slowing of contaminant migration trough the groundwater flow system due to *sorption* onto aquifer solids. Retardation delays the arrival and reduces the maximum concentration of a solute plume.

Sorption: several chemical and electrical processes by which a solute adheres to a solid surface. Sorption processes move molecules of contaminant from groundwater (the aqueous phase) to the aquifer material (the solid phase). If chemical conditions change, the sorbed solute can become a source of contamination to groundwater, desorbing from the aquifer solids back to the aqueous phase.

Specific Capacity: A measure of a wells productivity, obtained by dividing the rate of discharge of water from the well by the drawdown of the water level in the well. Methods exist for estimating the transmissivity (hydraulic conductivity multiplied by the saturated thickness of the aquifer) of an aquifer from specific capacity values.

Travel Time: The time is takes a particle of groundwater to move from one point to another.

Unlithified: sediment that is not cemented, such as sand, gravel or clay deposits

Windows: large areas where an otherwise laterally extensive geologic unit is absent

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ABBREVIATIONS

AwwaRF	Awwa Research Foundation
^{14}C	carbon-14
CFC	chlorofluorocarbon
DC	direct current resistivity
DNAPL	dense non-aqueous phase liquid
DP	direct push
f_{oc}	fraction of organic carbon
Fm	Formation
ft	foot
GPR	ground penetrating radar
^{2}H	deuterium
^{3}H	tritium
HSA	hollow stem auger
ICC	integrated cell culture
K	hydraulic conductivity
K_v	vertical hydraulic conductivity
K_h	horizontal hydraulic conductivity
K_{bv}	bulk vertical hydraulic conductivity
L	liter
LNAPL	light non-aqueous phase liquid
m	meter
µm	micrometer
MCL	maximum contaminant level
MLS	multilevel monitoring system
n_e	effective porosity
NAPL	non-aqueous phase liquid
ohm-m	ohm-meters
^{18}O	oxygen-18
PCBs	poly chlorinated biphenyls
PCR	polymerase chain reaction
RT	reverse transcription

TCE	trichloroethylene
TEM	time domain electromagnetics
SF^6	sulfur hexafluoride
SMOW	standard mean ocean water

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