The Design, Performance, and Analysis of Slug Tests, 2nd Ed

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Preface – First Edition

"What do I do with data like these?"

About six years ago, that simple question started me down the path that led to this book. My colleagues and I frequently found ourselves working with slug-test data that could not be readily analyzed with the commonly used methods. When we turned to the literature for assistance, we discovered few answers for those confronted with nonideal data. In fact, other than the useful, but not widely available, literature reviews of Chirlin (1990) and Boak (1991), we could not find a single general reference to which field practitioners could go for answers to practical questions about slug tests. Although the need for such a reference was widely recognized, no one seemed prepared to invest the time required to put the necessary material together. Finally, in a moment of frustration, I decided to take a stab at it.

This book is primarily designed to be a practical reference text. However, in the guise of a practical reference, this book also addresses some fundamental problems currently limiting the utility of information obtained from slug tests. Most groundwater scientists and engineers would agree that without more attention to data-acquisition methodology, the considerable promise of numerical models will never be realized. The slug test can potentially provide very useful information about the transmissive and storage properties of a unit, and their variations in space, on a scale of relevance for a variety of modeling investigations. Unfortunately, however, much of the data currently being obtained from slug tests is, and often rightfully so, viewed with considerable skepticism. This book is my attempt to place the slug test on sounder theoretical and procedural grounds with the goal of improving both the actual and perceived quality of information obtained with the technique. Although this book should certainly not be considered as the final word on the topic, I hope it can serve as a useful reference for the near future.

I am the only author of this book, and thus solely responsible for its contents. However, the research that underlies this effort should not be construed as the product of my labors alone. Many individuals contributed to various aspects of this work. Of particular note are my long-time colleagues at the Kansas Geological Survey, Carl McElwee and John Healey. Carl and I have worked together for a number of years on slug tests, as is evident by our coauthorship of several publications on the technique. Our cooperation in this and related work has been an extremely positive influence on my career. John Healey, our field hydrogeologist par excellence here at the Kansas Geological Survey, has been the source of much advice and assistance on the practical aspects of the methodology. John's background in the drilling industry was of particular assistance in preparation of Chapter 2. I also want to acknowledge the contributions of Geoff Bohling of the Kansas Geological Survey and Gil Zemansky of Compass Environmental. Geoff was the primary author of the

Suprpump analysis package, variants of which I used to perform many of the analyses discussed in this book. Sunday morning jogs with Gil have been the source of invaluable information about current practices in the consulting industry.

Many students at the University of Kansas provided field support for this work. These include Wenzhi Liu, Xiaosong Jiang, Tianming Chu, Yahya Yilmaz, Kristen Stanford, and Zafar Hyder. I would particularly like to cite the contribution of Wenzhi Liu. The careful reader will note that many of the tests presented as examples in this book were performed between late September and mid-November, a period during which the weather in Kansas can be particularly fickle. As a result, Wenzhi and I often ended up working under conditions that were considerably less than ideal. His good humor and ability to withstand the cold, wind, and dust without complaint were greatly appreciated.

I would also like to acknowledge the contributions of several individuals who kindly shared with me the products of their work. Kevin Cole of the University of Nebraska spent all-too-many hours generating the results presented in Tables 5.5, 6.3, and 6.4. Abraham Grader of Pennsylvania State University also went beyond the call of duty to generate simulation results that were an important contribution to Chapter 10. Frank Spane of Pacific Northwest Laboratory provided a copy of the DERIV program and valuable advice drawn from his extensive experience with various slug-test methods. Srikanta Mishra of Intera and Chayan Chakrabarty of Golder and Associates were both quite helpful in providing unpublished/in-press manuscripts.

I would also like to thank several individuals whose contributions were of a less-tangible nature. Bruce Thomson of the University of New Mexico provided friendship and excellent restaurant recommendations for the "Duke City" in the early stages of this project. Vitaly Zlotnik of the University of Nebraska was quite helpful with pithy comments and as a font of Russian aphorisms, the meaning of which I honestly never understand (fortunately, "ah, yes" seems to be the appropriate response in most cases). Rex Buchanan, Rich Sleezer, and cohorts provided editorial comments and comic relief in the final stages of this project. Finally, I would like to acknowledge the invaluable contributions of three individuals in the administration of the Kansas Geological Survey: Lee Gerhard, Larry Brady, and Don Whittemore. As a result of their efforts, the Kansas Geological Survey has certainly been an exciting place to pursue research in applied hydrogeology.

Although the above individuals all made important contributions to this effort, the most significant contributions were those of my family. This book could not have been written without the wholehearted support of my wife, Yun, and our children, Bill and Mei. Yun displayed much forbearance in allowing me the all-too-many nights and weekends of work that were needed to complete the book, while also serving as expert draftsperson and as all-purpose spiritual advisor. I greatly look forward in the coming months to spending much more time with Yun and the gang, and much less time with this computer.

Lawrence, Kansas
March 15, 1997

Preface – Second Edition

It has been more than 22 years since I wrote the preceding paragraphs. In the intervening period, significant progress has been made in many areas related to slug tests. This second edition was motivated by the need to incorporate these new developments, and most chapters have been extensively rewritten to reflect them. In particular, Chapters 4, 6–8, and 10–13 have been thoroughly revised. Additional field examples have been included and all graphics in the book have been redone. The ultimate objective of this effort was to have a practical reference text that is better positioned to stand the test of time.

A number of individuals made significant contributions to this second edition. Glenn Duffield, the developer of the AQTESOLV well-test analysis software and my long-time partner in continuing education courses, provided important assistance with software for the evaluation of all of the major analysis methods discussed in the book and with detailed review comments on the book draft. Glenn's AQTESOLV software has been a key element in the transfer of promising methods from the research arena to widespread field use and in making the analysis guidelines proposed here easy to implement. My colleague for the last 30 years at the Kansas Geological Survey, Geoff Bohling, provided important assistance in reviving rusty FORTRAN programs. Our long-time graphics artist at the Survey, Mark Schoneweis, created all of the schematic figures. In addition, my Survey colleagues Steve Knobbe, Ed Reboulet, and Gaisheng Liu assisted in the collection of field data for Figures 7.2 and 8.7A–B. Steve Knobbe also provided helpful review comments for Chapter 7. Duane Hampton of Western Michigan University kindly reviewed the LNAPL baildown test material. Xiuyu Liang of Southern University of Science and Technology generously provided the software for the evaluation of the Liang et al. (2018) solution for slug tests in unconfined aquifers, which was helpful in the assessment of the impact of the water table boundary condition. I have taught more than 40 short courses on slug tests in the last 20 years, most of which were organized by Dan Kelleher of Midwest Geosciences. That experience helped keep me abreast of the issues of most importance in practice and led me to include a list of eight steps that are critical for the success of a program of slug tests in the final chapter. I thank Dan for his commitment to organizing quality continuing education opportunities for practicing professionals.

As with the first edition, this second edition would not have been possible without the assistance of my wife, Yun, who has been the central figure in my life since we met on a cold gray afternoon in Beijing in March 1982. Although our children, Bill and Mei, have long since ventured out into the world, the weekend time required for this project did throw a wrench into many planned activities. Yun's continued support and helpful "oversight" were invaluable for bringing this effort to a successful completion.

Lawrence, Kansas
June 5, 2019

About the Author

James Johnson Butler, Jr. is a senior scientist with the Geohydrology Section of the Kansas Geological Survey at the University of Kansas. He holds a B. S. in geology from the College of William and Mary, and a M.S. and Ph.D. in applied hydrogeology from Stanford University. His primary research interests include high-resolution subsurface characterization, well responses to natural and anthropogenic stresses, and assessment of aquifers that support irrigated agriculture. Jim was the 2007 Darcy Distinguished Lecturer of the National Ground Water Association and the 2009 recipient of the Pioneers in Groundwater Award of the Environmental and Water Resources Institute of the American Society of Civil Engineers. He has served on the editorial board of five technical journals, has taught continuing education workshops and short courses on four continents, and has held visiting researcher positions at Stanford University, Universitat Politècnica de València, the University of Tübingen, Sandia National Laboratory, and the Institute of Geology of the State Seismological Bureau.

1 Introduction

In virtually all groundwater investigations, one needs to have an estimate of the transmissive nature of the subsurface units that are the focus of study. In hydrogeology, the transmissive nature of the media is characterized by the parameter termed hydraulic conductivity or, in its fluid-independent form, intrinsic permeability. A large number of experimental techniques have been developed over the years to provide estimates of the hydraulic conductivity of subsurface material. These techniques range from laboratory-based permeameter or grain-size analyses to large-scale multiwell pumping tests. In the last few decades, a field technique for the in situ estimation of hydraulic conductivity known as the slug test has become increasingly popular, especially among scientists and engineers working at sites of suspected groundwater contamination. It is no exaggeration to say that tens of thousands of slug tests are performed each year in the United States alone. Despite the heavy utilization of this technique by the environmental industry, the scientific literature, for many years, was focused on theoretical models for the analysis of slug-test data, with relatively little attention paid to the application of the method in practice. Given the prevalence of the technique and the economic magnitude of the decisions that can be based on its results, the objective of the first edition of this book was to fill the pressing need for a text to which the field investigator could refer for answers to questions concerning all aspects of the design, performance, and analysis of slug tests. This second edition updates the earlier material and expands the topical coverage with new developments that have come to the fore in the intervening twenty-one years between editions.

THE SLUG TEST—WHAT IS IT?

The slug test is a deceptively simple approach in practice. It essentially consists of measuring the recovery of head (water level) in a well after a near-instantaneous change in head at that well (a nearby observation well can also be used in certain situations). Figure 1.1 is a pair of schematic cross sections that illustrate the major features of a slug test. In the standard configuration, a test begins with a sudden change in water level in a well (Figure 1.1A). This can be done, for example, by rapidly introducing a solid object (hence the term "slug") or equivalent volume of water into the well (or removing the same), causing an abrupt increase (or decrease) in water level. Following this sudden change, the water level in the well returns to static conditions as water moves out of the well (as in Figure 1.1B) or into it (when change is a decrease in water level) in response to the gradient imposed by the head change. An example record of head changes with time during a slug test is given in Figure 1.2. These head changes, which are termed the response data, can be used to estimate the hydraulic conductivity of

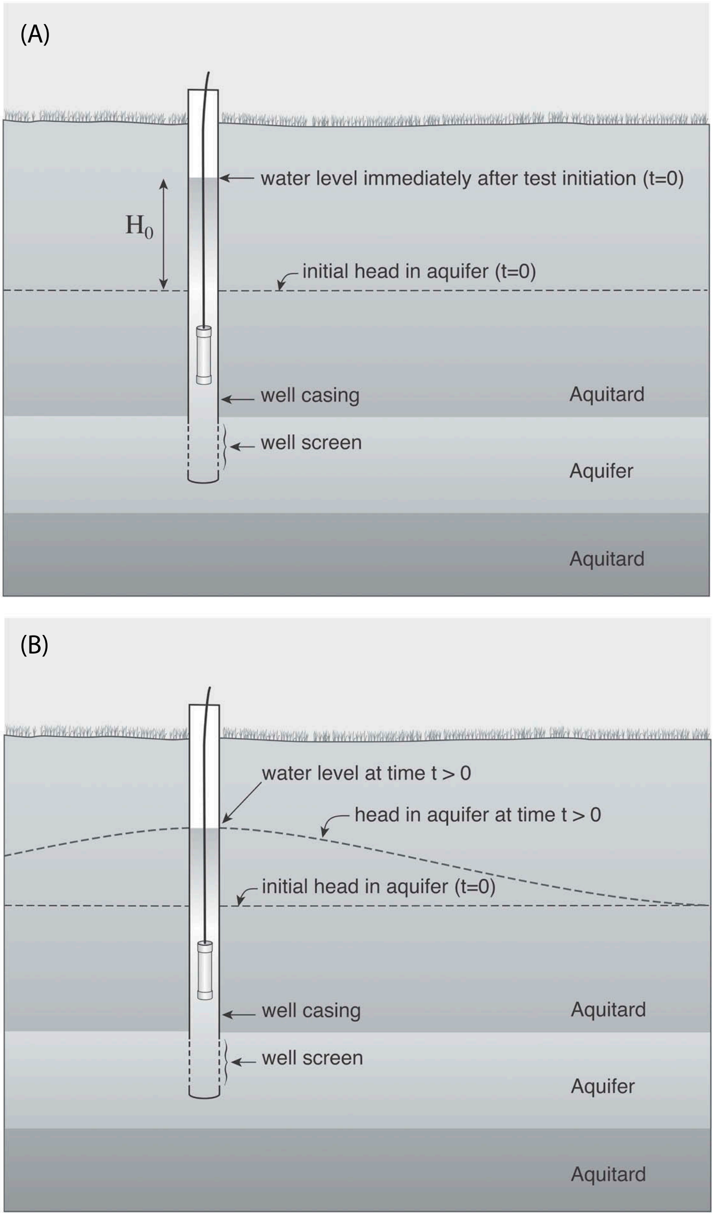

FIGURE 1.1 Schematic cross sections depicting a slug test in a well screened in a confined aquifer: A) Condition immediately after test initiation; B) Condition some time after initiation (slug test initiated at time t = 0 by rapid insertion of solid object (slug) into the water column, H_0 is the measured initial displacement (water-level change produced by slug insertion), figures not to scale).

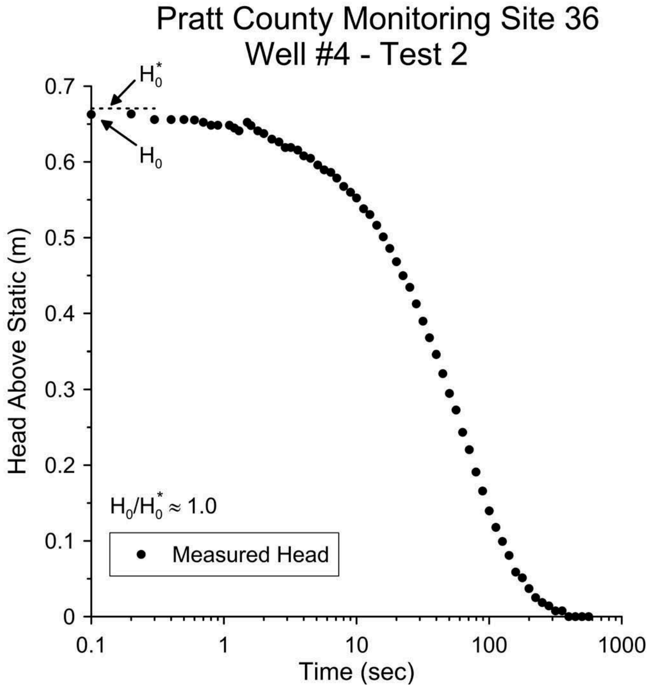

FIGURE 1.2 Plot of head above static versus log time since test began for a slug test performed in well #4 at monitoring site 36 in Pratt County, Kansas (H_0 is the measured initial displacement in the well and H_0^* is the expected initial displacement for the test).

the formation through comparisons with theoretical models of the well-formation response to the slug-induced disturbance. In theory, slug tests can often also be used to obtain an estimate of the formation's ability to release or accept water into storage; this storage capability of the media is characterized in hydrogeology by the specific storage parameter. However, given the realities of the field, one can have little confidence in the estimate of specific storage resulting from a slug test. In contrast to pumping tests, slug tests are rapid and affect a relatively small volume of the formation, so little information about slow-to-develop flow mechanisms (e.g., pore drainage or multiporosity flow) or formation boundaries can be obtained.

The hydraulic conductivity estimates obtained from slug tests can be used for a variety of purposes. At sites of groundwater contamination, test estimates can be used to predict the subsurface movement of a contaminant, to design remediation schemes, and to plan multiwell pumping tests for obtaining more information about the large-scale hydraulic behavior of the subsurface units of interest. In water supply investigations, slug-test estimates are primarily utilized for the design of large-scale pumping tests, for estimation of flow in formations of low hydraulic conductivity, and for the assessment of the hydraulic connection between an observation well and the formation in which it is screened. In near-surface agricultural applications, parameter estimates obtained with the slug test, which is termed the auger hole or piezometer method in the agricultural and soils literature, can be used to design drainage systems for lowering shallow water tables. In petroleum and coalbed-methane applications, parameter estimates from slug tests and the closely related drill-stem test are primarily used to help assess the potential for economic exploitation of a particular petroleum- or methane-producing horizon. In addition, scientists and engineers from a wide variety of other disciplines use slug tests in their work. For example, wetland hydrologists will commonly use slug tests to obtain hydraulic conductivity estimates for water- and solute-balance calculations, while glaciologists often use slug tests to obtain estimates of the hydraulic conductivity of the zones at the base of glaciers.

WHY IS IT SO PREVALENT?

The slug test has become such a frequently used field method as a result of its considerable logistical and economic advantages over alternative approaches. The most important of these advantages are:

a) Low cost: Both in terms of labor and equipment, the slug test is considerably less expensive than alternative approaches. A program of slug tests can be performed by one, or at most, two people using a pressure transducer, data logger, and minor amounts of auxiliary equipment. When the cost of the equipment is spread over a large number of tests, the cost per test is extremely low;
b) Simple: As described earlier, the slug test is a very simple procedure. One initiates a test by a variety of means and then just measures the changes in head through time. Other than the possibility of having to clean equipment before moving to the next well, little else is required in the field;
c) Relatively rapid: The duration of a slug test is short in formations that would be classified as aquifers. In less-permeable formations, the test duration can be made relatively short through appropriate well and test design;
d) Useful in tight formations: The slug test may be one of the best options for obtaining in situ estimates in formations of low hydraulic conductivity. In such so-called "tight" units, it may not be practical to perform constant-rate pumping tests because of the difficulty of maintaining a low discharge rate. Although constant-head injection tests are often performed in the geotechnical industry, their logistics and the need to introduce water into the formation make them less attractive for environmental applications. Historically, laboratory testing of core samples has been widely used for obtaining information about the properties of low-conductivity media. This technique,

however, has become less common because of the concern that core samples may not provide information on a large enough scale to detect the existence of preferential flow paths, which can be important conduits for fluid movement in such settings. The difficulty of obtaining an "undisturbed" sample and concerns about possible differences between the vertical and horizontal components of hydraulic conductivity have further limited the use of core-based approaches;

e) No water required: An important advantage of slug tests at sites of suspected groundwater contamination is that the technique can be configured so that no water is removed from or added to the well during a test. This can be done by initiating a test through the addition or removal of a solid slug to/from the water column (Figure 1.1), the pressurization-depressurization of the air column in the well, etc.;

f) Provides information on spatial variability: A program of slug tests can be designed to obtain information about spatial variations in hydraulic conductivity at a scale of relevance for contaminant transport investigations. In contrast, conventional pumping tests will provide large-scale volumetric averages of hydraulic properties, which may be of limited use in transport investigations. By performing a series of slug tests at discrete vertical intervals within individual wells and/or single tests in relatively closely spaced wells, important information can be obtained about the vertical and horizontal variations in hydraulic conductivity at a site;

g) Perceived straightforward analysis: The analysis of response data from slug tests is generally perceived to be straightforward. Analysis methods involve fitting theoretical responses (type curves) or straight lines to plots of field data. The later-time processes and boundary effects that can make the analysis of large-scale pumping tests so involved generally have little to no impact on slug tests.

BUT SKEPTICISM ABOUNDS ...

Despite the heavy usage by the environmental industry, the slug test is viewed skeptically by many groundwater scientists and engineers. The origin of this skepticism is the discrepancy that is often observed between hydraulic conductivity estimates obtained from slug tests and those obtained from other elements of the field investigation (e.g., geologic and geophysical logs, pumping tests, etc.). Although spatial variability and the different scales at which the various estimates were obtained can explain a portion of the observed discrepancy, three other factors may be primarily responsible for this situation. First, well-development activities are often minimal at monitoring wells, the primary type of wells in which slug tests are performed. The result is that slug tests can be heavily impacted by drilling-induced disturbances and products of biochemical action. Countless field examples demonstrate the significant impact of insufficient well development on slug tests. Unlike pumping tests, that impact can be difficult to remove during the analysis process. Second, slug tests can be heavily impacted by choices made during well construction. For example, slug tests in formations of moderate-to-high hydraulic conductivity can yield artificially low conductivity estimates when performed in wells with relatively small casing radii and/or screen openings (slot size). Third, the simplicity of the technique seems to foster a rather casual attitude among some involved in the performance and analysis of slug tests. The result is that many of the assumptions underlying conventional analysis techniques are not upheld, introducing a considerable degree of error into the final parameter estimates. Fortunately, greater attention to details of well construction and development, coupled with the application of more care to all aspects of the test process, can greatly improve this situation. However, as will be emphasized throughout this book, the effects of incomplete well development and nonideal well construction may be difficult to avoid. Thus, the hydraulic conductivity estimate obtained from a slug test should virtually always be viewed as a lower bound on the actual hydraulic conductivity of the formation in the vicinity of the well. This lower bound can be a very reasonable estimate of formation conductivity with appropriate field and analysis procedures.

PURPOSE OF THIS BOOK

The major purpose of this book is to provide a series of practical guidelines that should enable reasonable parameter estimates to be obtained from slug tests on a consistent basis. Four critical themes will be emphasized throughout the presentation:

1. Importance of well development: Slug tests are extremely sensitive to near-well disturbances, so it is no exaggeration to say that the success of a program of slug tests critically depends on the effectiveness of well-development activities. Repeat slug tests and preliminary screening analyses will be the primary approaches recommended here for the evaluation of the effectiveness of development activities;
2. Importance of well construction: Slug tests can be extremely sensitive to the details of well construction, so the success of a program of slug tests, particularly in formations of moderate-to-high hydraulic conductivity, heavily depends on choices made during well design and construction. Preliminary screening analyses and specialized analysis procedures will be the primary means recommended here for identifying and partially compensating for nonideal well construction;
3. Importance of test design: A program of slug tests must be designed so that the viability of the key assumptions underlying conventional analysis methods can be assessed for a particular set of tests. Repeat slug tests and comparison of the measured (H_0) and expected (H_0^*) values for the initial head change will be the primary means recommended here for this assessment;

4. Importance of appropriate analysis procedures: The analyst must strive to extract as much information as possible about the well-formation configuration from the analysis of slug-test data. Stepwise analysis procedures (i.e., repeat analyses using different representations of the well-formation configuration) will be the primary means recommended here for getting the most from the analysis phase of a test program.

The importance of these themes will be demonstrated with numerous field examples. Unless noted otherwise, these examples are drawn from field studies done by the author while at the Kansas Geological Survey.

In keeping with this book's role as a reference text, the target audience is very broad, ranging from the practicing professional to the academically oriented investigator. An attempt was made to provide a thorough discussion of all practical issues involved in the design, performance, and analysis of slug tests. For example, each analysis method is clearly outlined in a step-by-step manner, after which the procedure is illustrated with a field example and all major practical issues related to the application of that technique are discussed. For the more theoretically minded reader, the mathematical models underlying all major techniques are presented, thus allowing the assumptions incorporated in the various analysis methods to be better understood. Relevant references are provided to supplement the discussion in the text. The ultimate objective of the presentation is to help the reader explore a given topic to virtually any depth that is desired.

OUTLINE

The core of this book consists of the following eleven chapters (Chapters 2 to 12). Each chapter is designed to be a relatively self-contained unit, so that the reader can refer to a particular section without necessarily needing to read the other chapters. The major points of a chapter are summarized in the form of a series of practical guidelines that are given at the conclusion of each chapter or, in the case of the analysis methods, presented in a separate summary chapter (Chapter 12).

Chapter 2 focuses on the design of a series of slug tests, the all-too-often neglected phase of a test program. Details of well construction and development pertinent to slug tests are discussed, with an emphasis placed on approaches for assessing the sufficiency of well-development activities. The use of repeat slug tests and the $H_0 - H_0^*$ comparison to assess the viability of the assumptions underlying most analysis methods are also discussed.

Chapter 3 focuses on issues associated with the performance of slug tests, the most practical aspects of a test program. The primary types of equipment that are used for the measurement and storage of head data are described. The most common methods for initiating a slug test are then presented, and the strengths and weaknesses of each are highlighted. A particular emphasis is placed on assessing each method with respect to the relative speed of test initiation and the potential for obtaining accurate estimates of both H_0 and H_0^*.

Chapter 4 focuses on the pre-analysis processing of response data, a critical step for preparing data for formal analysis and for assessing the appropriateness of the assumptions invoked by the analysis methods. A special emphasis is placed on the processing of data collected with pressure transducers.

Chapters 5 through 12 focus on the techniques used for the analysis of test data. All major methods for the analysis of slug tests in confined and unconfined formations are described. Examples are heavily utilized to illustrate how a particular approach should be applied. An emphasis is placed on the use of stepwise analysis procedures to obtain as much information as possible about the well-formation configuration. These procedures are described in detail in Chapter 12.

Chapter 13 highlights the importance of eight key elements of a test program and then briefly summarizes the major themes of the book. The book concludes with an appendix defining notation used in the text followed by a list of cited references.

A SHORT WORD ON TERMINOLOGY ...

Over the last fifty years, a fair amount of terminology has been developed with respect to slug tests. Unfortunately, certain aspects of this terminology have led to some confusion and misunderstandings. Two aspects are worth noting here. First, there has been an effort to differentiate between tests that are initiated by a sudden rise or a sudden drop in the head (water level) in a well, that is, tests in which the direction of the slug-induced flow (into/out of the well) differs. For tests initiated by a sudden rise in water level (Figure 1.1A), the terms *falling-head*, *slug*, slug-in, and *injection tests* have been most commonly used in the literature. For tests initiated by a sudden drop in water level, the terms *rising-head*, *bail-down*, *bailer*, slug-out, and *withdrawal tests* have been most commonly used. The terms *response test* and *variable-head tests* have been used for both situations. In this book, the term *slug test* is used for all tests in which the focus of interest is the response to a near-instantaneous change in head at a well. If there is a need to differentiate between tests on the basis of the direction of the slug-induced flow, the modifiers rising-head and falling-head are employed. Second, the head change initiating a slug test has been called the slug, the initial displacement, H_0, and the slug-induced disturbance, among other things. In this book, the terms *initial displacement* and H_0 are primarily used to designate this initial head change.

One final issue of semantics concerns what to call the individuals who are primarily responsible for the planning, performance, and analysis of a program of slug tests. The most appropriate designation, “groundwater scientists and engineers”, is a bit too lengthy for repetitive use, so more succinct terminology must be employed. Thus, the terms “hydrogeologist” and “hydrologist” are used interchangeably here to designate the group of scientists and engineers from a multitude of backgrounds who are charged with the task of carrying out/overseeing a program of slug tests.

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