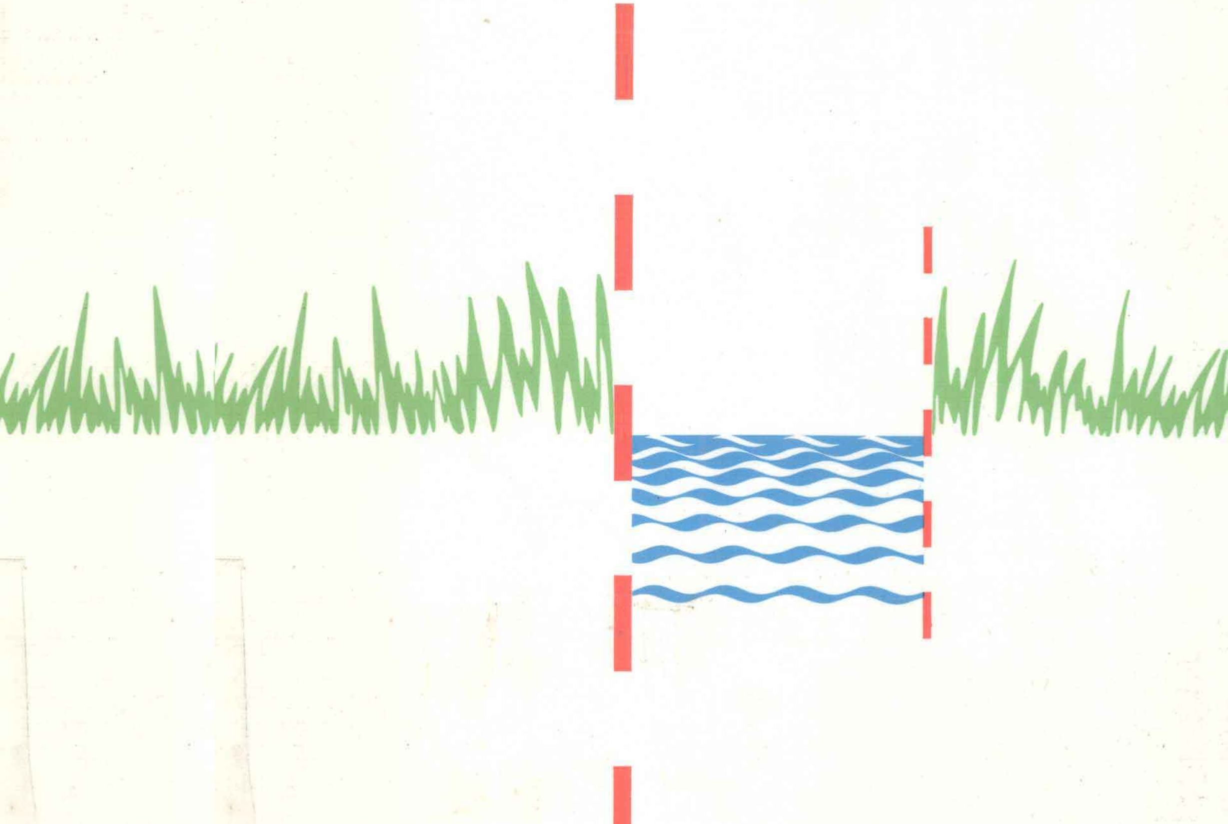
ILRI publication 47

Analysis and Evaluation of Pumping Test Data

Second Edition (Completely Revised)

G.P. Kruseman
N.A. de Ridder

With assistance from
J. M. Verweij



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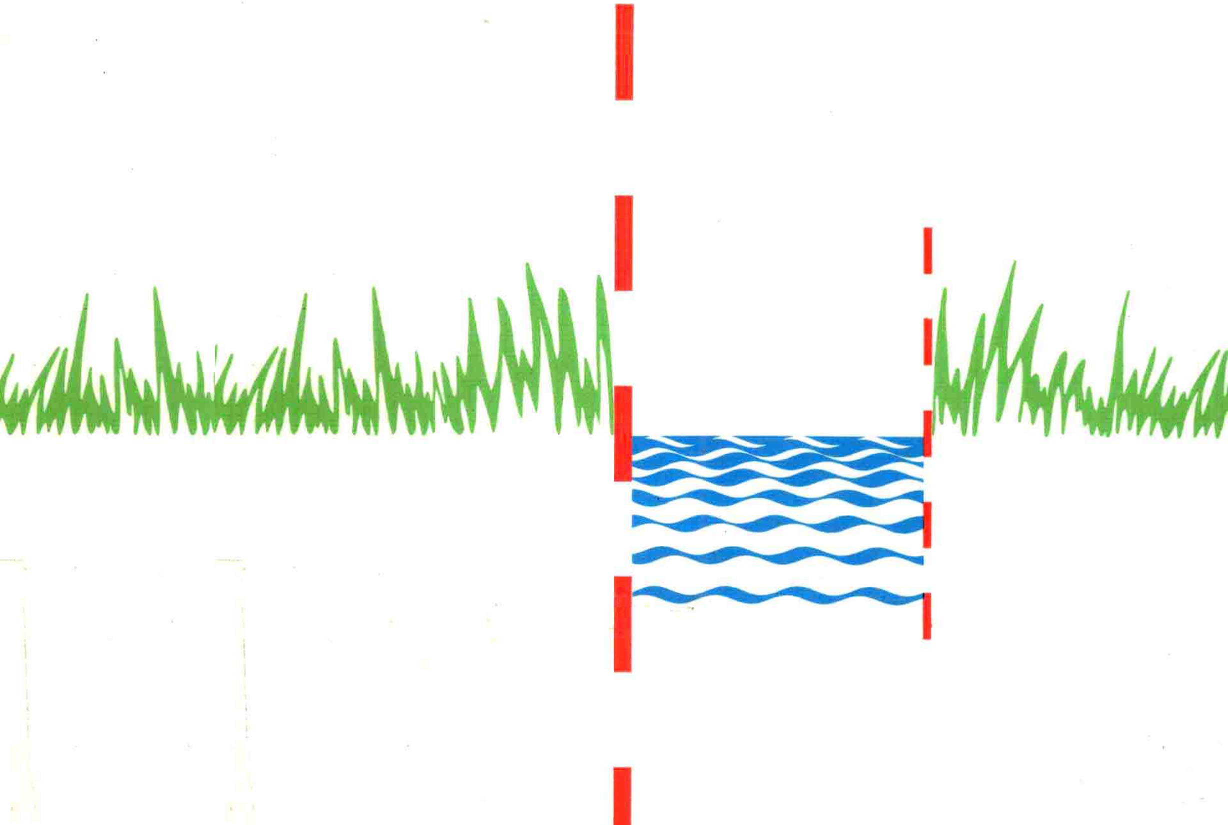

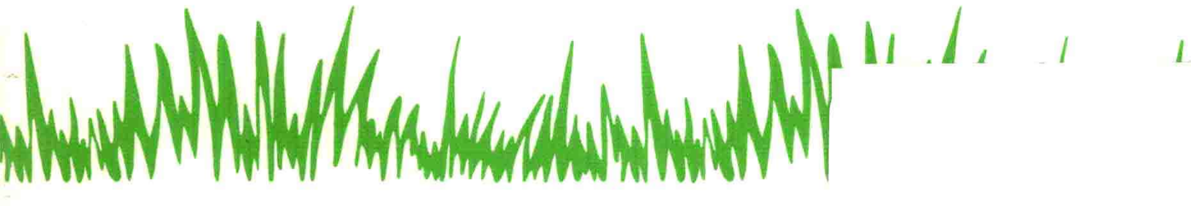

International Institute for Land Reclamation a
Wageningen, The Netherlands

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The first edition of this book appeared as No. 11 in the series of Bulletins of the International Institute for Land Reclamation and Improvement/ILRI. Because the ILRI Bulletins have now been discontinued, this completely revised edition of the book appears as ILRI Publication 47.

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Preface

This is the second edition of *Analysis and Evaluation of Pumping Test Data*. Readers familiar with the first edition and its subsequent impressions will note a number of changes in the new edition. These changes involve the contents of the book, but not the philosophy behind it, which is to be a practical guide to all who are organizing, conducting, and interpreting pumping tests.

What changes have we made? In the first place, we have included the step-drawdown test, the slug test, and the oscillation test. We have also added three chapters on pumping tests in fractured rocks. This we have done because of comments from some of our reviewers, who regretted that the first edition contained nothing about tests in fractured rocks. It would be remiss of us, however, not to warn our readers that, in spite of the intense research that fractured rocks have undergone in the last two decades, the problem is still the subject of much debate. What we present are some of the common methods, but are aware that they are based on ideal conditions which are rarely met in nature. All the other methods, however, are so complex that one needs a computer to apply them.

We have also updated the book in the light of developments that have taken place since the first edition appeared some twenty years ago. We present, for instance, a more modern method of analyzing pumping tests in unconfined aquifers with delayed yield. We have also re-evaluated some of our earlier field examples and have added several new ones.

Another change is that, more than before, we emphasize the intricacy of analyzing field data, showing that the drawdown behaviour of totally different aquifer systems can be very similar.

It has become a common practice nowadays to use computers in the analysis of pumping tests. For this edition of our book, we seriously considered adding computer codes, but eventually decided not to because they would have made the book too voluminous and therefore too costly. Other reasons were the possible incompatibility of computer codes and, what is even worse, many of the codes are based on 'black box' methods which do not allow the quality of the field data to be checked. Interpreting a pumping test is not a matter of feeding a set of field data into a computer, tapping a few keys, and expecting the truth to appear. The only computer codes with merit are those that take over the tedious work of plotting the field data and the type curves, and display them on the screen. These computer techniques are advancing rapidly, but we have refrained from including them. Besides, the next ILRI Publication (No. 48, *SATEM: Selected Aquifer Test Evaluation Methods* by J. Boonstra) presents the most common well-flow equations in computerized form. As well, the International Ground-Water Modelling Centre in Indianapolis, U.S.A., or its branch office in Delft, The Netherlands, can provide all currently available information on computer codes.

Our wish to revise and update our book could never have been realized without the support and help of many people. We are grateful to Mr. F. Walter, Director of TNO Institute of Applied Geoscience, who made it possible for the first author and Ms

Hanneke Verwey to work on the book. We are also grateful to Brigadier (Retired) K.G. Ahmad, General Manager (Water) of the Water and Power Development Authority, Pakistan, for granting us permission to use pumping test data not officially published by his organization.

We also express our thanks to Dr J.A.H. Hendriks, Director of ILRI, who allowed the second author time to work on the book, and generously gave us the use of ILRI's facilities, including the services of Margaret Wiersma-Roche, who edited our manuscript and corrected our often wordy English. We are indebted to Betty van Aarst and Joop van Dijk for their meticulous drawings, and to Trudy Pleijsant-Paes for her patience and perseverance in processing the words and the equations of the book. Last, but by no means least, we thank ILRI's geohydrologist, Dr J. Boonstra, for his discussion of the three chapters on fractured rocks and his valuable contribution to their final draft.

We hope that this revised and updated edition of *Analysis and Evaluation of Pumping Test Data* will serve its readers as the first edition did. Any comments anyone would care to make will be received with great interest.

G.P. Kruseman
N.A. de Ridder

Contents

1 Basic concepts and definitions

When working on problems of groundwater flow, the geologist or engineer has to find reliable values for the hydraulic characteristics of the geological formations through which the groundwater is moving. Pumping tests have proved to be one of the most effective ways of obtaining such values.

Analyzing and evaluating pumping test data, however, is as much an art as a science. It is a science because it is based on theoretical models that the geologist or engineer must understand and on thorough investigations that he must conduct into the geological formations in the area of the test. It is an art because different types of aquifers can exhibit similar drawdown behaviours, which demand interpretational skills on the part of the geologist or engineer. We hope that this book will serve as a guide in both the science and the art.

The equations we present in this book are from well hydraulics. We have omitted any lengthy derivations of the equations because these can be found in the original publications listed in our References. With some exceptions, we present the equations in their final form, emphasizing the assumptions and conditions that underlie them, and outlining the procedures that are to be followed for their successful application.

'Hard rocks', both as potential sources of water and depositories for chemical or radioactive wastes, are receiving increasing attention in hydrogeology. We shall therefore be discussing some recent developments in the interpretation of pumping test data from such rocks.

This chapter summarizes the basic concepts and definitions of terms relevant to our subject. The next chapter describes how to conduct a pumping test. The remaining chapters all deal with the analysis and evaluation of pumping test data from a variety of aquifer types or aquifer systems, and from tests conducted under particular technical conditions.

1.1 Aquifer, aquitard, and aquiclude

An aquifer is defined as a saturated permeable geological unit that is permeable enough to yield economic quantities of water to wells. The most common aquifers are unconsolidated sand and gravels, but permeable sedimentary rocks such as sandstone and limestone, and heavily fractured or weathered volcanic and crystalline rocks can also be classified as aquifers.

An aquitard is a geological unit that is permeable enough to transmit water in significant quantities when viewed over large areas and long periods, but its permeability is not sufficient to justify production wells being placed in it. Clays, loams and shales are typical aquitards.

An aquiclude is an impermeable geological unit that does not transmit water at all. Dense unfractured igneous or metamorphic rocks are typical aquicludes. In nature, truly impermeable geological units seldom occur; all of them leak to some extent, and must therefore be classified as aquitards. In practice, however, geological units can be classified as aquicludes when their permeability is several orders of magnitude lower than that of an overlying or underlying aquifer.

The reader will note that the above definitions are relative ones; they are purposely imprecise with respect to permeability.

1.2 Aquifer types

There are three main types of aquifer: confined, unconfined, and leaky (Figure 1.1).

1.2.1 Confined aquifer

A confined aquifer (Figure 1.1A) is bounded above and below by an aquiclude. In a confined aquifer, the pressure of the water is usually higher than that of the atmosphere, so that if a well taps the aquifer, the water in it stands above the top of the aquifer, or even above the ground surface. We then speak of a free-flowing or artesian well.

1.2.2 Unconfined aquifer

An unconfined aquifer (Figure 1.1B), also known as a watertable aquifer, is bounded below by an aquiclude, but is not restricted by any confining layer above it. Its upper boundary is the watertable, which is free to rise and fall. Water in a well penetrating an unconfined aquifer is at atmospheric pressure and does not rise above the watertable.

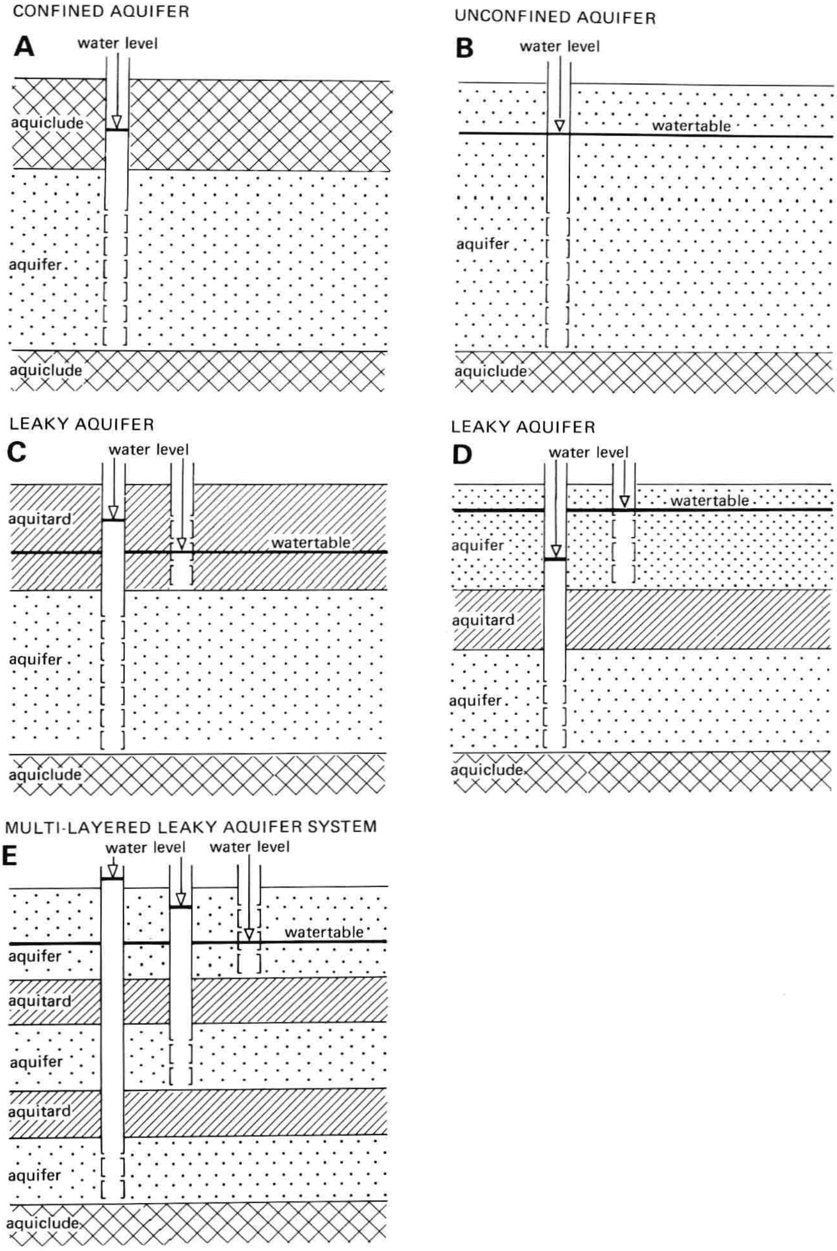
1.2.3 Leaky aquifer

A leaky aquifer (Figure 1.1C and D), also known as a semi-confined aquifer, is an aquifer whose upper and lower boundaries are aquitards, or one boundary is an aquitard and the other is an aquiclude. Water is free to move through the aquitards, either upward or downward. If a leaky aquifer is in hydrological equilibrium, the water level in a well tapping it may coincide with the watertable. The water level may also stand above or below the watertable, depending on the recharge and discharge conditions.

In deep sedimentary basins, an interbedded system of permeable and less permeable layers that form a multi-layered aquifer system (Figure 1.1E), is very common. But such an aquifer system is more a succession of leaky aquifers, separated by aquitards, rather than a main aquifer type.

1.3 Anisotropy and heterogeneity

Most well hydraulics equations are based on the assumption that aquifers and aquitards are homogeneous and isotropic. This means that the hydraulic conductivity is the same throughout the geological formation and is the same in all directions (Figure



CONFINED AQUIFER

UNCONFINED AQUIFER

LEAKY AQUIFER

LEAKY AQUIFER

MULTI-LAYERED LEAKY AQUIFER SYSTEM

Figure 1.1 Different types of aquifers
A. Confined aquifer
B. Unconfined aquifer
C. and D. Leaky aquifers
E. Multi-layered leaky aquifer

1.2A). The individual particles of a geological formation, however, are seldom spherical so that, when deposited under water, they tend to settle on their flat sides. Such a formation can still be homogeneous, but its hydraulic conductivity in horizontal direction, K_h, will be significantly greater than its hydraulic conductivity in vertical direction, K_v (Figure 1.2B). This phenomenon is called anisotropy.

The lithology of most geological formations tends to vary significantly, both horizontally and vertically. Consequently, geological formations are seldom homogeneous. Figure 1.2C is an example of layered heterogeneity. Heterogeneity occurs not only in the way shown in the figure: individual layers may pinch out; their grain size may vary in horizontal direction; they may contain lenses of other grain sizes; or they may be discontinuous by faulting or scour-and-fill structures. In horizontally-stratified alluvial formations, the K_h/K_v ratios range from 2 to 10, but values as high as 100 can occur, especially where clay layers are present.

Anisotropy is a common property of fractured rocks (Figure 1.2D). The hydraulic conductivity in the direction of the main fractures is usually significantly greater than that normal to those fractures.

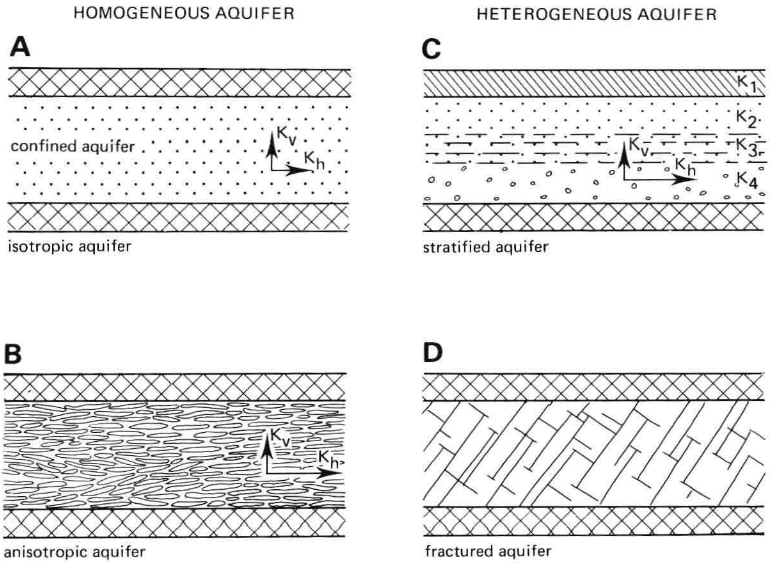


Figure 1.2 Homogeneous and heterogeneous aquifers, isotropic and anisotropic
A. Homogeneous aquifer, isotropic
B. Homogeneous aquifer, anisotropic
C. Heterogeneous aquifer, stratified
D. Heterogeneous aquifer, fractured