Selected Contributions to Ground-Water Hydrology by C.V. Theis, and a Review of His Life and Work

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Selected Contributions to Ground-Water Hydrology by C.V. Theis, and a Review of His Life and Work

Edited by ALFRED CLEBSCH

Contributions by C.V. THEIS, CHARLES A. APPEL,
ALFRED CLEBSCH, and
ROBERT R. WHITE

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FOREWORD

C.V. Theis wrote "A Primer on Anisotropy" in the early 1970's to provide a tool to those hydrogeologists not conversant with tensor mathematics for the analysis of problems dealing with anisotropic distribution of hydraulic conductivity. At least one reviewer of the manuscript then felt that the treatment was too complex to be considered a "primer," but Theis looked upon it as an elementary technique that was far from "state of the art," even at the time. It is interesting to note that this, his last truly technical paper, is drawn to a great extent from the physical analogy with crystallography, whereas his best-known work, first published in 1935, "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage," was based on another physical analogy, the unsteady flow of heat in a homogeneous solid.

"Aquifers, Ground-Water Bodies and Hydrophers" was written in 1983, but he dictated changes and additions to it only a few weeks before his death in July 1987. It was his attempt to clarify points of confusion in the use of "aquifer" and illustrates his quest for precision in terminology, as well as his outlook on hydrogeology. While there is considerable merit to the arguments advanced, they do not represent the official position of the Geological Survey with respect to the terminology under discussion.

This publication is neither a memorial volume nor a complete collection of Theis' unpublished writings. He left several other unpublished manuscripts, some of which would have been noteworthy contributions to ground-water hydrology had they been published soon after they were written.

Although Theis' retirement in 1970 marked the end of his formal career with the Geological Survey, he continued the association as a rehired annuitant and volunteer worker for another 17 years. His correspondence file of this twilight period of his career is filled with advice and counsel to numerous hydrogeologists, young and old, in many parts of the globe; indeed, one of his most important contributions to hydrogeology may have been through his responses to these requests for review and comment.

C.V. Theis was the recipient of many honors, fortunately during his lifetime, by scientific colleagues—deservedly so. He spent a remarkably long and intensely active career solving small to medium water-supply and waste-disposal problems that provided grist for the mill of a prodigiously fertile intellect.

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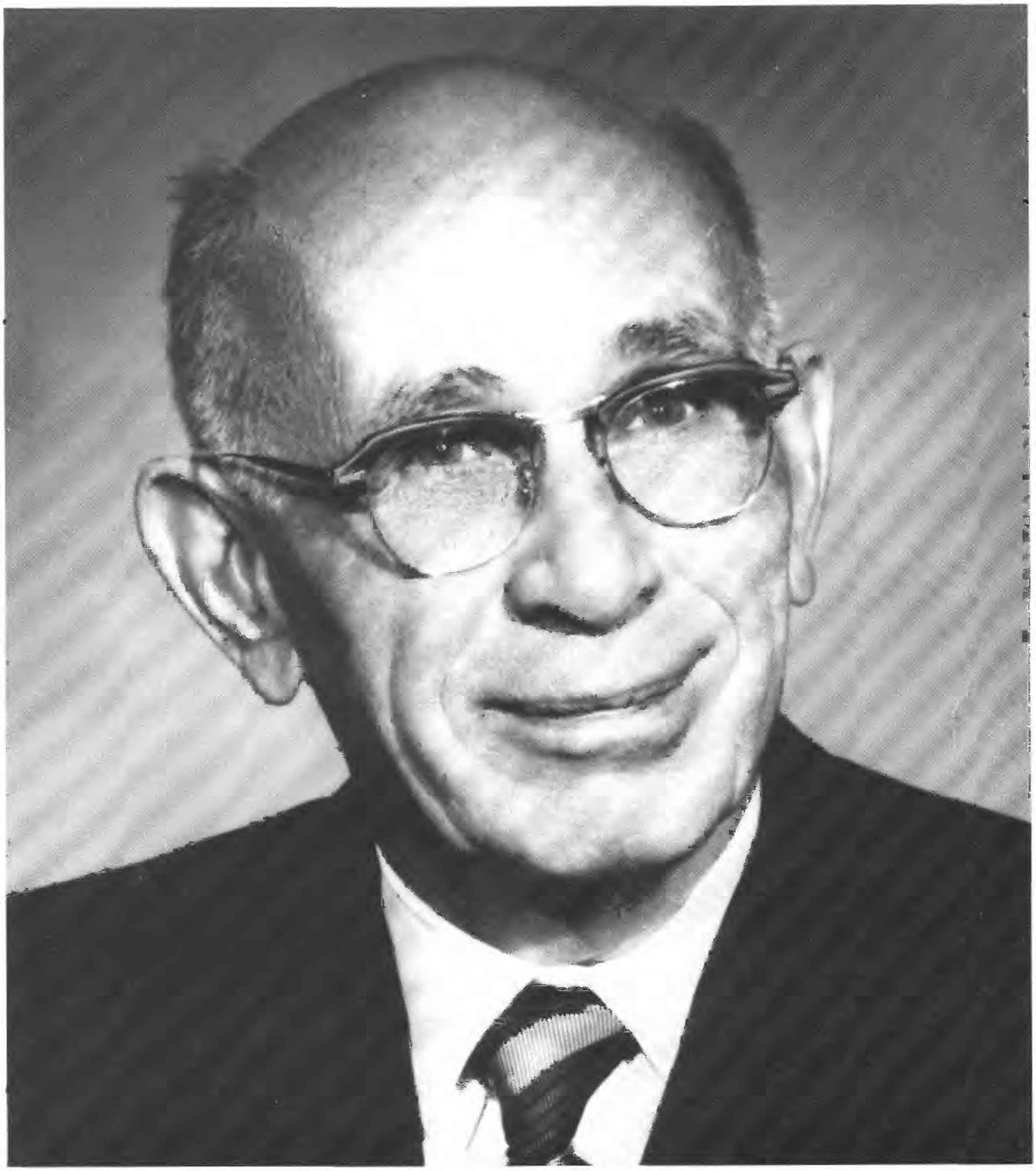
PHILIP COHEN
Chief Hydrologist
U.S. Geological Survey



CHARLES V. THEIS

1900-1987

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Bibliography of C.V. Theis
Compiled by Alfred Clebsch

Selected Contributions to Ground-Water Hydrology By C.V. Theis, and a Review of His Life and Work

Edited by Alfred Clebsch

Abstract

This publication highlights two previously unpublished papers by C.V. Theis; each is augmented with a discussion that explains why he wrote the paper, attempts to discern why he did not publish the paper, and amplifies the information with reference material not included by Theis.

"A Primer on Anisotropy" was written in the early 1970's to provide practicing hydrogeologists of the day with a method of analyzing ground-water problems involving anisotropic hydraulic-conductivity distribution without using tensor mathematics. The equations were developed for horizontal flow through dipping beds with differing conductivities parallel and perpendicular to the bedding and for flow through dipping beds having three different hydraulic conductivities, one perpendicular to the bedding and two others parallel to the bedding, at an angle to the strike of the beds.

Although most colleagues who reviewed the primer in the early 1970's encouraged its publication enthusiastically, at least one suggested the addition of some examples in which the method would be demonstrated. Handwritten notes from Theis' files indicate that he may have worked on some examples and possibly other additions to the paper. The comments by Charles A. Appel include some examples of the primer's use and augment the presentation with references to relevant published papers, both those available to Theis but not cited by him, and subsequent publications.

"Aquifers, Ground-Water Bodies, and Hydrophers" was written in the early 1980's as an attempt to clarify the semantic and conceptual confusion in the use of the term *aquifer*, applied by some investigators to the saturated part of a permeable formation and by others to the entire permeable formation. The physical distinction between the *aquifer* and the *ground-water body* is emphasized, and the term *hydropher* is proposed to describe the saturated part of a permeable formation. Theis' interest in and familiarity with the French literature on ground water was the basis for a discussion of the French usage, which eschews the term *aquifer*. The analysis and critique of Theis' paper explains the 1835 paper from which *aquifer* was reportedly derived, and provides further justification for the term *hydropher.*

Theis' more important contributions to ground-water hydrology were outgrowths of his solutions to small local water problems based on field investigations. The biographical sketch, drawing extensively from a partial autobiography that Theis had dictated, reveals both the reasons for and the intellectual processes that led to his development of the nonequilibrium concept of ground-water hydraulics. The sketch also describes the background of the man, reviews his career, and portrays the admiration and respect he elicited from his colleagues and associates.

The magnitude of Theis' contribution to the science of ground-water hydrology, to the appraisal of the water resources of New Mexico, and to the early research on ground disposal of radioactive wastes is evident from the bibliography of his writings, which includes 168 reports, many of them unpublished. The evolution of his thinking about the role of geologic inhomogeneities in mass transport, conceptualized but not quantified, was the major contribution of the latter part of his career.

INTRODUCTION

Given the length of his active career and his stature as a hydrogeologist, the number of papers published in the formal scientific literature by C.V. Theis is not large. However, in addition to those published works, Theis wrote numerous reports on problem-solving investigations that he conducted as a member of the U.S. Geological Survey for 40 years, and as a rehired annuitant or volunteer worker for 17 years after his official retirement. These commonly provided the foundation for more fundamental papers included in his published works. He also left at least six unpublished manuscripts that were complete or nearly so; these were identified in the course of sorting, screening, and cataloging Theis' files, library, and other papers in 1988 and 1989. The six manuscripts were reviewed by Geological Survey hydrogeologists as possible candidates for inclusion in this Water-Supply Paper. In addition to the six, numerous notebook entries and other notes probably would have been worthy of publication at the time they were written or needed some additional development of the ideas contained therein. The time available for reviewing the files did not permit a sufficiently detailed analysis of these materials to consider publishing them.

After careful technical review of the six candidate manuscripts, two were selected for inclusion in this publication. The two papers, which form the core of this publication, were written after his formal retirement from the Geological Survey. Although close associates from his earlier years may view these two as inferior to his contributions made during the 1930's and 1940's, they do illustrate his continued intellectual vitality and interest in contributing to his chosen field of science. Both papers contain important lessons for the practicing hydrogeologist, even though neither should be viewed as a complete, final product. The four that were not selected for publication are discussed in the introduction to Theis' bibliography. Two were outgrowths of work done in the 1940's; the other two were written in the 1960's.

When this publication was being planned, consideration was given to making it a retrospective, or memorial, volume by republishing some of Theis' earlier works along with the late-career contributions and some unpublished manuscripts written in the 1940's. This would have had the advantage of demonstrating, more fully than has been accomplished with this collection, the total range of Theis' thinking and writings on earth-science topics, but it would have necessitated seeking commentaries from several experts in additional fields of specialization. It would have resulted in further delay in making Theis' last works available. Furthermore, the selection of previously published works would have been a rather subjective endeavor for which the editor did not consider himself qualified. The landmark 1935 paper, "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage" has been republished at least four times, once since work began on this collection of papers.

To hydrologists, geologists, and others interested in ground water, the contributions of the first part of the career of C.V. Theis are well known. During the middle third of his career, he was deeply involved in short-term problem-solving investigations and had responsibilities for planning and supervising the work of others, so although he was no less productive, his work during that period is less well known. During the "twilight" of his career, after his formal retirement from the Geological Survey in 1970, he maintained a strong and active interest in ground-water geology and hydrology until his death in 1987. During this period, his contributions to hydrogeology probably were reflected in his influence on ground-water hydrologists who sought his wise counsel on scientific problems rather than from his own scientific output. His correspondence files reveal an experienced, thoughtful, and compassionate scientist sharing his wisdom with others who wanted his advice. If a problem showed signs of careful and thorough analysis and thought, the guidance was likely to be paternal, insightful, and philosophical. A poorly reasoned hypothesis, or worse yet, one that showed a lapse in scientific integrity by ignoring valid data that failed to corroborate the author's preferred hypothesis, could provoke an acerbic and scornful critique.

It will become apparent from reading the accompanying discussions of the two papers by Theis in this volume that he was not overly diligent in searching the published literature in connection with writing the papers. To a degree this may be true for his earlier works as well. The commentary on "A Primer on Anisotropy" demonstrates that several prior papers dealt with similar problems. Theis apparently did not see these papers because he did not cite them. However, Theis did not need the results of those papers in order to write the "primer," and to include them would have made it more complicated and perhaps less easily used. Customarily, Theis either derived from first principles the mathematics he needed for a given paper, or sought the help of experts to do so.

The analysis and critique of "Aquifers, Ground-Water Bodies, and Hydrophers" points out that Theis was well aware of the purported source of the term *aquifer*—indeed, he questioned the accuracy of the attribution—but he did not consult the paper. Although this apparent laxity might be viewed as a failing, perhaps it can be overlooked for a writer in his 80's.

The biographical sketch and the bibliography are included in this volume to show what kind of man Theis was, to present a summary of his professional activities, and to demonstrate the volume and range of his written output, especially for those parts of his career that are not well represented by publications in the recognized scientific literature.

Throughout his career, Theis did much of his best work alone. He often made a practice of writing something, setting it aside for a while, and coming back to it later to rejudge the ideas and reasoning to make sure they withstood the test of more objective scrutiny, at least scrutiny after a period free from the rigors of immediate involvement with a new development. Sometimes this was done of necessity, because in many instances he was not closely associated with colleagues who could help him through the process of critical review. He felt that new ideas were difficult to present in a way that would assure their acceptance by scientific colleagues, and that the first step toward this acceptance was for the author to assure himself that the ideas were scientifically sound and clearly expressed. Partly as a consequence of this *modus operandi*, some of his manuscripts languished in his files or notebooks until they were reviewed by others and judged to be worthwhile contributions. Several of his shorter works on groundwater hydraulics fall into this category.

The introduction to the bibliography is intended to call attention to the range of topics on which Theis wrote and to highlight papers that represent significant contributions that have not been published or otherwise made available. It should not be looked upon as an exhaustive commentary or as a substitute for annotations on each entry. The introduction also gives the location of unpublished material and of Theis' scientific and personal files.

The custom of listing cited references at the end of each chapter has been modified somewhat for this publication. Inasmuch as all Theis' citable papers are listed in the bibliography, the reference lists for individual chapters do not contain papers by Theis that have been cited; the citations can be found in the Theis bibliography.

Critical review of this report by Ted Arnow and W.R. Hotchkiss is acknowledged with thanks. Their criticisms led to the correction of a number of internal inconsistencies and to general technical and editorial improvement. Final preparation of the text was done by Theresa Jo Lane. Significant contributions to text preparation also were made by Judith Cornwell, Douglas Shubert, Bobbie Cloud, and others. Line drawings were prepared by H.M. Grossman and Derald Dunagan. General advice and editorial review by John Flager are acknowledged with sincere gratitude. Other review and processing assistance is acknowledged in individual chapters.

A Primer on Anisotropy

By C.V. Theis

<u>Editor's note:</u> **The format and editorial style of this chapter may not follow the conventions used in most publications of the U.S. Geological Survey, for the following reasons: (1) The paper was written originally as a tutorial document, and the format is intended to facilitate such use; (2) the paper was written two decades ago, and Survey conventions have been modified somewhat in the intervening period; and (3) the author was an exceptionally thoughtful and precise writer, and it has been deemed useful to preserve his style insofar as possible.**

INTRODUCTION

Nearly all models dealing with ground-water flow are based on the assumption of a homogeneous and isotropic aquifer. Consideration of nonhomogeneous conditions requires a detailed knowledge of the aquifer not usually feasible to acquire, and when known, can only be analyzed numerically or by an analog model. On the other hand, many anisotropic aquifers can be considered as isotropic aquifers by a simple distortion in scale.

The common practice of drawing flow lines in nature perpendicular to the potentiometric contours is generally justified only as probably being approximately correct and as being the best one can do with insufficient data. Only when many pumping tests give consistent data in all directions from the pumping well can we have confidence in the isotropy of the area. One assumption to be particularly guarded against is that vertical movement of the water necessarily occurs if a vertical gradient is shown by one or two pairs of potentials at different depths in the aquifer. Because generally our data are too few to prove isotropy, the effects of anisotropy should be clearly in the mind of every field worker.

Such hydraulically anisotropic aquifers may result from the processes of sedimentation, such as the deposition of channel materials in an alluviating valley, or as bars and spits in a transgressing sea; or by the overlapping of basalt flows, tending to give continuity of porous zones farther in one direction than another; or by solution in limestone along a preferred direction, resulting from either structural control or from movement of the water to a linear discharge area such as a river. Such alinement of nonhomogeneous features may be treated as an anisotropic condition when the scale of the problem studied is such that a considerable number of such similarly oriented, elongated nonhomogeneities are included. While theoretically the movement could be accurately predicted if the potentials in each local homogeneous and isotropic lens were known, it is generally impossible to obtain such information.

The treatment of anisotropic hydraulic conductivity in the many texts available to the geohydrologist presupposes a knowledge of mathematics beyond the training of many if not most of those at present studying field hydrogeology. It may be worthwhile to consider the treatment of anisotropy from a rather elementary standpoint, for these phenomena are without doubt much more common than we realize.

Probably all aquifers that can be considered on the proper scale to be homogeneous can also be considered to have orthorhombic[1] anisotropy, that is, the anisotropy is characterized by three mutually perpendicular principal conductivity axes in the directions of greatest, least, and intermediate conductivity. In any plane including two of the axes, these will be the directions of greatest and least conductivity. In many types of aquifers two of the conductivities are equal and in the familiar isotropic model all of them are equal. These can be considered special cases of the general class of anisotropic aquifers.

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[1]<u>**Editor's note:**</u> In his initial draft of this paper, Theis used *orthorhombic* to characterize a flow system with three mutually perpendicular conductivity axes each having a different conductivity value. One colleague reviewer who was not familiar with crystallography questioned the term and suggested *orthotropic* as an alternative. Theis adopted the suggestion and followed that usage in subsequent drafts. In 1990, reviewers of the May 1974 draft questioned the use of *orthotropic*, pointing out that in this context it is imprecise and that in its common usage, in a botanical context, it is not an appropriate term. Theis' original usage has been restored.

LIST OF SYMBOLS

Symbol	Dimensions	Explanation
A	—	Angle of dip of strata (Sections B, C)
B	—	Angle in bedding plane between strike and first conductivity axis (Section C)
B'	—	Angle in bedding plane between strike and axis of greatest bedding-plane conductivity (Section C)
		Hydraulic Conductivity
K	LT^{-1}	in isotropic aquifer
K_x, K_y, K_z	LT^{-1}	in x, y, and z directions, respectively (Section A)
K_c	LT^{-1}	perpendicular to bedding plane (Sections B, C)
K_p	LT^{-1}	parallel to bedding plane (Section B)
K_g	LT^{-1}	along axis of greatest bedding-plane conductivity (Section C)
K_s	LT^{-1}	along axis of smallest bedding-plane conductivity (Section C)
K_1, K_2, K_3	LT^{-1}	along axes $1, 2, 3$ respectively (Section C)
K_{xy}	LT^{-1}	Conductivity coefficient giving component of flux along axis x caused by component of hydraulic gradient on axis y. Other coefficients involve all combinations of axes, 9 in all (Sections B, C)
h	L	Head
Q	L^3T^{-1}	Discharge rate across a given cross section (Section A)
q	LT^{-1}	Specific discharge or flux
q_x, q_y, q_z	LT^{-1}	Components of flux along x, y, and z respectively
r	L	Radius
s	L	Drawdown
S	—	Storage coefficient
S_s	L^{-1}	Specific storage
T	L^2T^{-1}	Transmissivity
t	T	Time

A. CONDUCTIVITY AXES VERTICAL AND HORIZONTAL

Probably the most common type of anisotropic aquifer consists of horizontally bedded sediments. If coarser lenses or bars alined in one direction exist in the aquifer and if finer grained sediments are interlayered with the coarser beds, three hydraulic conductivities must be recognized. These can be alined with the horizontal and vertical axes, x, y, and z. A horizontally lying succession of lava beds might also be so treated. Practically all problems involving this type of anisotropy can be reduced to isotropic problems.

The equation of continuity or the statement of mass balance, as derived in text books on ground water, is

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = -\frac{S_s \partial h}{\partial t} \qquad \text{(A 1)}$$

For homogeneous, isotropic media Darcy's law $q = \frac{-K\partial h}{\partial l}$ can be inserted in this equation to obtain:

$$\frac{K\partial^2 h}{\partial x^2} + \frac{K\partial^2 h}{\partial y^2} + \frac{K\partial^2 h}{\partial z^2} = S_s \frac{\partial h}{\partial t}$$

or

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{K}\frac{\partial h}{\partial t} .$$

Now suppose the conductivities are different along the three mutually perpendicular axes. Where this is so, $q_x = -K_x \frac{\partial h}{\partial x}$, $q_y = -K_y \frac{\partial h}{\partial y}$, and $q_z = -K_z \frac{\partial h}{\partial z}$. When these are inserted the equation of continuity becomes

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} . \qquad \text{(A 2)}$$

Suppose we take the ratio of these conductivities to some entirely arbitrary conductivity. Call this arbitrary standard of conductivity K_a.

$$\text{Let } \alpha^2 = \frac{K_x}{K_a}, \beta^2 = \frac{K_y}{K_a}, \gamma^2 = \frac{K_z}{K_a} , \qquad \text{(A 3)}$$

$$\frac{\partial}{\partial x}\left(\alpha^2 K_a \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(\beta^2 K_a \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(\gamma^2 K_a \frac{\partial h}{\partial z}\right) = \frac{S_s \partial h}{\partial t}.$$

If the medium is homogeneous, as assumed,

$$\frac{\partial^2 h}{\partial (x/\alpha)^2} + \frac{\partial^2 h}{\partial (y/\beta)^2} + \frac{\partial^2 h}{\partial (z/\gamma)^2} = \frac{S_s}{K_a}\frac{\partial h}{\partial t} . \qquad \text{(A 4)}$$

This gives us an isotropic equation in the new transformed space variables x/α, y/β, z/γ with diffusivity K_a / S_s.

Let us consider what the other hydraulic properties are in this model. We shall use K', S'_s, etc., for these properties in the transformed model. Consider a small element of real space Δx, Δy, Δz and a similar element in the transformed space $(\Delta x / \alpha)$, $(\Delta y / \beta)$, $(\Delta z / \gamma)$. We require that the flow across each model will be the same.

$$-\Delta Q_x = \Delta y \Delta z K_x \frac{\Delta h}{\Delta x} = \frac{\Delta y}{\beta} \frac{\Delta z}{\gamma} K'_x \frac{\Delta h}{\Delta x / \alpha}$$

$$\text{and } K'_x = \frac{\beta\gamma K_x}{\alpha} = \frac{\beta\gamma\alpha^2 K_a}{\alpha} = \alpha\beta\gamma K_a \qquad \text{(A 5)}$$

$$-\Delta Q_y = \Delta x \Delta z K_y \frac{\Delta h}{\Delta y} = \frac{\Delta x}{\alpha} \frac{\Delta z}{\gamma} K'_y \frac{\Delta h}{\Delta y / \beta}$$

$$K'_y = \frac{\alpha\gamma}{\beta} K_y = \frac{\alpha\gamma}{\beta} \beta^2 K_a = \alpha\beta\gamma K_a = K'_x . \qquad \text{(A 6)}$$

$$\text{Similarly, } K'_z = \alpha\beta\gamma K_a = K'_x = K'_y .$$

The transformed space is evidently isotropic with the conductivity $K' = \alpha\beta\gamma K_a$. Inasmuch as the diffusivity is $K_a / S_s = K' / S'_s$, $S'_s = \alpha\beta\gamma S_s$ if $K' = \alpha\beta\gamma K_a$.

Independently, we may say that the quantity of water derived from the real and the transformed space element must be the same with a given decrease in head, $(\Delta x \Delta y \Delta z)\, \Delta h S_s = \frac{\Delta x}{\alpha} \frac{\Delta y}{\beta} \frac{\Delta z}{\gamma} \Delta h S'_s$, so that

$S'_s = \alpha\beta\gamma S_s$.

The transformed space is, therefore, isotropic with these values of specific storage and conductivity. Introducing the values of α, β, and γ,

$$K' = K_a \left(\frac{K_x K_y K_z}{K_a^3} \right)^{\frac{1}{2}} , \qquad \text{(A 7)}$$

$$S'_s = S_s \left(\frac{K_x K_y K_z}{K_a^3} \right)^{\frac{1}{2}} , \qquad \text{(A 8)}$$

$$K' / S'_s = K_a / S_s . \qquad \text{(A 9)}$$

It is convenient to take the arbitrary conductivity, K_a, as unit conductivity. If we do so and express K in metric units, as an example,

$$K'\,(\mathrm{m/day}) = 1\,(\mathrm{m/day})\sqrt{\frac{K_x K_y K_z\,(\mathrm{m/day})^3}{1\,(\mathrm{m/day})^3}}$$

$$S'_s\,(\mathrm{m}^{-1}) = S_s\,(\mathrm{m}^{-1})\sqrt{\frac{K_x K_y K_z\,(\mathrm{m/day})^3}{1\,(\mathrm{m/day})^3}}.$$

These equations are sometimes shortened to $K' = \sqrt{K_x K_y K_z}$ and $S'_s = S_s\sqrt{K_x K_y K_z}$, which, because of the omitted K_a, are dimensionally inconsistent, although they represent the numerical procedure. In the following two paragraphs this shortened form is used and it must be assumed that introduction of the arbitrary conductivity into the equations will make them dimensionally consistent.

If we consider only horizontal components of flow, the z terms vanish and we can substitute transmissivities and coefficients of storage into the equation for conductivities and specific storage. If T_a is unity, we obtain

$$T' = \sqrt{T_x T_y} \text{ and } S' = \sqrt{T_x T_y}S \,;\; x' = \frac{x}{\sqrt{T_x}} \text{ and } y' = \frac{y}{\sqrt{T_y}};\; T'/S' = 1/S\,.$$

If $K_x = K_y$, as perhaps in horizontal bedded sediments in which there is no preferential direction of flow in the plane of the bedding, $K' = K_x\sqrt{K_z}$ and $S'_s = K_x\sqrt{K_z}S_s$.

The final stage in this process is to transfer the isopotentials and flow vectors for any particular stress imposed on the aquifer from the transformed model back to the real space. In the isotropic transformed model, flow vectors are perpendicular to isopotentials but in the real model flow vectors are not perpendicular to isopotentials except along the axes themselves. To illustrate this, let us consider a 2-dimensional case; that is, we consider the flow as essentially horizontal.

Suppose we aline our axes with the y-axis having a conductivity 1/4 that of the x-axis. Let us have a river at an angle of 45 degrees with these axes, cutting through the aquifer. We will insert an image well to obtain the effect of recharge from the river. Our transformed space and our real space will then be as shown in figure A-1. The image well will not lie on a perpendicular to the river in real space. The central flux vector is at an angle to the river, and the flow lines enclosing one-half of the total flux, which form a circle in the transformed isotropic space, form an ellipse in real space.

Similarly, if we were mapping a cone of depression around a pumped well, the contours would be circles in the transformed space and ellipses in real space.

In the vicinity of a discharging well in an anisotropic aquifer it is evident that the drawdowns vary with the angle that the direction of the observation well makes with the principal axes of conductivity.

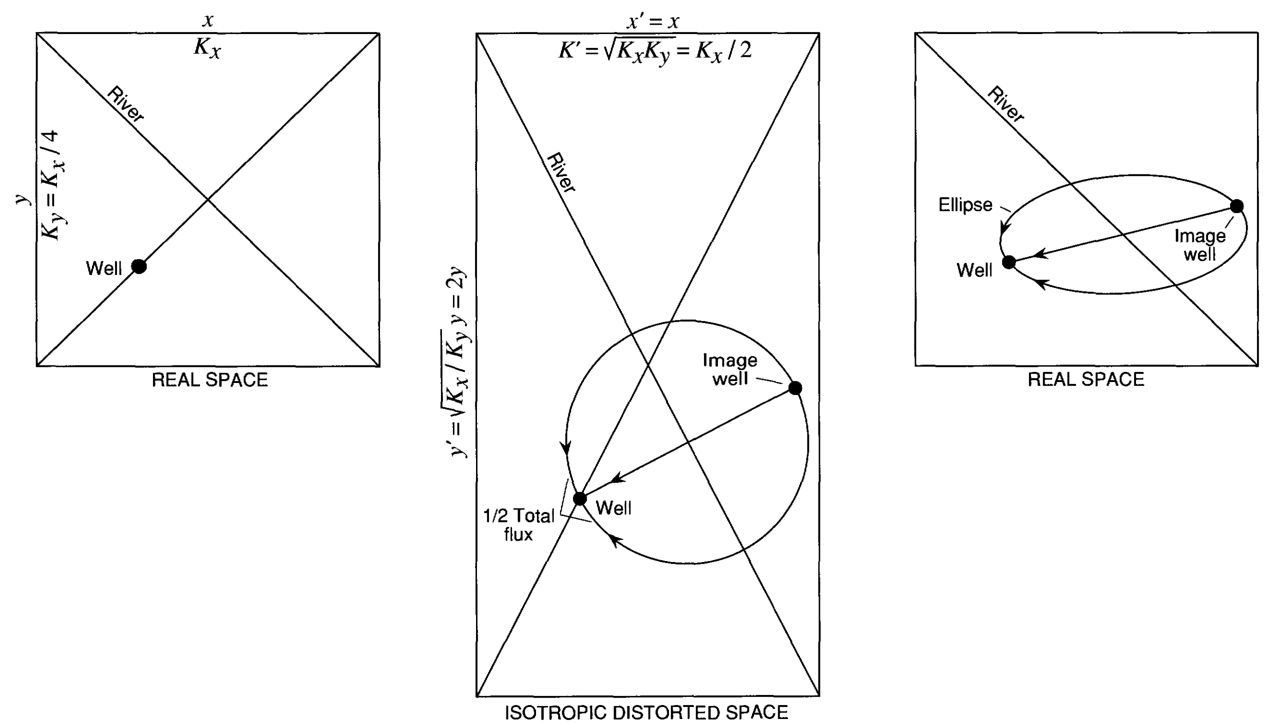


Figure A-1. A well near a river in an area having horizontal anisotropy.

In the transformed isotropic space the ordinary formulas for drawdowns around a discharging well apply.[1] As an instance, for 2-dimensional anisotropy in an aquifer with no leakage,

$$s = \frac{Q}{4\pi T'} W\left(\frac{(r')^2 S'}{4T't}\right).$$

---

[1]**Editor's note:** $W\left(\frac{r^2 S}{4Tt}\right)$ is the "well function" and represents the definite integral $\int_{\frac{r^2 S}{4Tt}}^{\infty} \left(\frac{e^{-\hat{u}}}{\hat{u}}\right) d\hat{u}$, in which $\hat{u}$ is a dimensionless variable of integration. It is the essential element in the "Theis equation," (see Theis, 1935b and 1938e) and describes the time-distance-drawdown relations in the vicinity of a well pumping at constant discharge in an isotropic medium. Theis also stipulated other limiting assumptions in its application to hydrologic problems. This modification (r', S', T') and equations A 10 - A 16 extend the concept to anisotropic conditions.

Substituting real space equivalents and assuming that x and y are the directions of the principal axes of conductivity;

$$s = \frac{Q}{4\pi\sqrt{T_x T_y}} W\left(\frac{\left(\frac{x^2}{T_x} + \frac{y^2}{T_y}\right)S}{4t}\right) \qquad \text{(A 10)}$$

$$= \frac{Q}{4\pi\sqrt{T_x T_y}} W\left(\frac{(T_y x^2 + T_x y^2)\,S}{4T_x T_y t}\right). \qquad \text{(A 11)}$$

Writing $T_x / T_y = N$,

$$s = \frac{Q}{4\pi T_y\sqrt{N}} W\left(\frac{(x^2 + Ny^2)\,S}{4NT_y t}\right). \qquad \text{(A 12)}$$

If θ is the angle between the x-axis and the direction of an observation well during a discharge test,

$$s = \frac{Q}{4\pi T_y\sqrt{N}} W\left[\frac{r^2(\cos^2\theta + N\sin^2\theta)\,S}{4NT_y t}\right] \qquad \text{(A 13)}$$

$$= \frac{Q}{4\pi T_y\sqrt{N}} W\left[\frac{r^2 S}{4T_y t}\left(1 + \frac{(1-N)\cos^2\theta}{N}\right)\right]. \qquad \text{(A 14)}$$

If T_r is the transmissivity in the direction from the pumping well to the observation well (Hantush and Thomas, 1966, p. 282),

$$\frac{1}{T_r} = \frac{\cos^2\theta}{T_x} + \frac{\sin^2\theta}{T_y}$$

$$= \frac{\cos^2\theta + N\sin^2\theta}{NT_y}. \qquad \text{(A 15)}$$

Equation A 13 can therefore be written

$$s = \frac{Q}{4\pi T_y\sqrt{N}} W\left(\frac{r^2 S}{4T_r t}\right). \qquad \text{(A 16)}$$

This is the form used by Hantush and Thomas.

B. FLOW THROUGH DIPPING STRATA

A common kind of anisotropic hydrology is movement across dipping beds in which the conductivity across the beds is generally much less than that along the bedding. In this section we shall consider the conductivity uniform in all directions parallel to the bedding.

Consider beds dipping at the angle A that have a hydraulic conductivity K_p, parallel to the bedding, and K_c, across, that is, perpendicular to the bedding. We place one K_p conductivity axis along the strike of the beds which we shall take as the y-axis. The other K_p axis will fall along the dip of the beds, which we shall designate the p-axis. The axis with K_c conductivity, designated c, will be perpendicular to the p-axis and also the y-axis. Consequently the p- and c-axes lie in the xz-plane.

The hydraulic gradient, which is the negative of the head gradient, must be represented by its components on axes x, y, and z, as $-\frac{\partial h}{\partial x}$, $-\frac{\partial h}{\partial y}$, and $-\frac{\partial h}{\partial z}$. Inasmuch as the y-axis (the strike axis) has the conductivity K_p, and as there are no x or z components of gradient along it, we may write for the component of flux in that direction,

$$-q_y = K_p \frac{\partial h}{\partial y}. \tag{B 1}$$

We may now turn our attention to the xz-plane, which is also the pc-plane. Our problem is to find the flux along the x- and z-axes. To do this, we project the $-\frac{\partial h}{\partial x}$ and $-\frac{\partial h}{\partial z}$ gradients onto the p- and c-axes each of which is characterized by a conductivity, and then project the fluxes so obtained back on the x- and z-axes.

These projections to the other set of axes do not change in any way either the direction or the magnitude of the hydraulic gradient or the flux vector. We shall designate the angles involved by the axes forming them, all angles being measured between the positive ends of the axes forming them, thus (xp), (xc), (zp), and (zc). We shall also deal exclusively with cosines, as these will give simpler and more consistent equations.

The components of flux along the p-axis, q_p, and the c-axis, q_c, will then be (see fig. B-1).

$$\left.\begin{aligned} -q_p &= K_p\left[\cos(px)\frac{\partial h}{\partial x} + \cos(pz)\frac{\partial h}{\partial z}\right] \\ -q_c &= K_c\left[\cos(cx)\frac{\partial h}{\partial x} + \cos(cz)\frac{\partial h}{\partial z}\right] \end{aligned}\right\}. \tag{B 2}$$

The components of these fluxes on the x- and z-axes are (fig. B-2)

$$\left.\begin{aligned} q_x &= q_p\cos(px) + q_c\cos(cx) \\ q_z &= q_p\cos(pz) + q_c\cos(cz) \end{aligned}\right\}. \tag{B 3}$$

Substituting the values for q_p and q_c from equation B 2, we have

$$\begin{aligned} -q_x &= K_p\cos(px)\left[\cos(px)\frac{\partial h}{\partial x} + \cos(pz)\frac{\partial h}{\partial z}\right] \\ &\quad + K_c\cos(cx)\left[\cos(cx)\frac{\partial h}{\partial x} + \cos(cz)\frac{\partial h}{\partial z}\right] \\ &= \left[K_p\cos^2(px) + K_c\cos^2(cx)\right]\frac{\partial h}{\partial x} \\ &\quad + \left[K_p\cos(px)\cos(pz) + K_c\cos(cx)\cos(cz)\right]\frac{\partial h}{\partial z} \end{aligned} \tag{B 4}$$

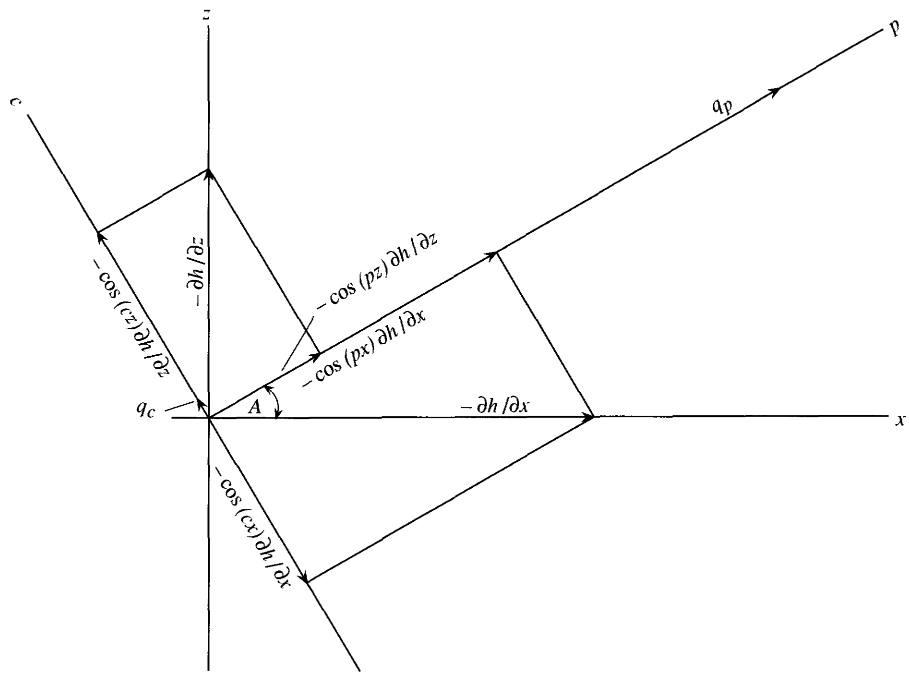


Figure B-1. Components of gradients and resulting fluxes on *p*- and *c*-axes.

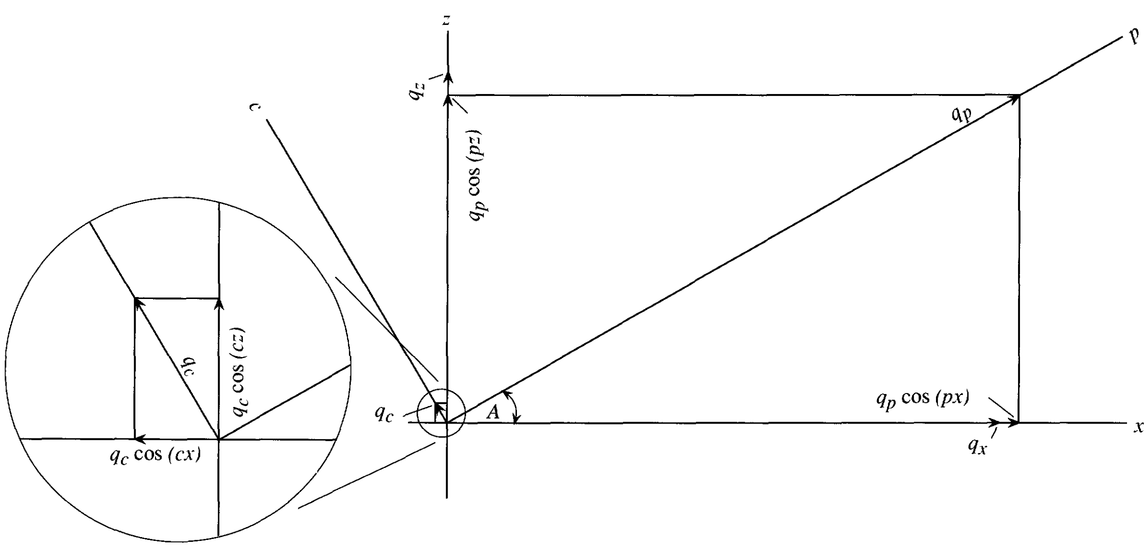


Figure B-2. Components of fluxes on *x*- and *z*-axes.

$$-q_z = \left[K_p \cos^2(pz) + K_c \cos^2(cz)\right]\frac{\partial h}{\partial z}$$

$$+\left[K_p \cos(pz) \cos(px) + K_c \cos(cz) \cos(cx)\right]\frac{\partial h}{\partial x}\,. \qquad \text{(B 5)}$$

It is convenient and customary to write these equations as

$$\left.\begin{aligned} -q_x &= K_{xx}\frac{\partial h}{\partial x} + K_{xz}\frac{\partial h}{\partial z} \\ -q_z &= K_{zx}\frac{\partial h}{\partial x} + K_{zz}\frac{\partial h}{\partial z} \end{aligned}\right\}, \qquad \text{(B 6)}$$

in which the various K's are *conductivity coefficients*, and in which the first subscript always denotes the direction of the component of flux being considered and the second subscript, the direction of the component of the hydraulic gradient being considered. Evidently,

$$\begin{aligned} K_{xx} &= K_p \cos^2(px) + K_c \cos^2(cx) \\ K_{xz} &= K_p \cos(px) \cos(pz) + K_c \cos(cx) \cos(cz) \\ K_{zx} &= K_p \cos(pz) \cos(px) + K_c \cos(cz) \cos(cx) = K_{xz}\,. \\ K_{zz} &= K_p \cos^2(pz) + K_c \cos^2(cz) \end{aligned} \qquad \text{(B 7)}$$

The simplicity of these conductivity coefficients should be noted. Each coefficient is the product of a conductivity times the cosine of the angle between its axis and the first subscript axis times the cosine of the angle between its axis and the second subscript axis plus a similar product involving the other conductivity. Note also that all signs on the right-hand side of all the equations preceding are positive. Note further that $K_{xz} = K_{zx}$.

These coefficients may now be transformed into expressions involving only the angle of dip, A, which is the angle (px). First consider movement of water against the dip, that is the angle (px) lies in the first quadrant.

$$K_{xx} = K_p \cos^2 A + K_c \cos^2(90° + A)$$

$$K_{xz} = K_{zx} = K_p \cos A \cos(90° - A) + K_c \cos(90° + A) \cos A$$

$$K_{zz} = K_p \cos^2(90° - A) + K_c \cos^2 A.$$

Remembering that cos (90° – A) = sin A and cos (90° + A) = –sin A,

$$\left.\begin{aligned} K_{xx} &= K_p \cos^2 A + K_c \sin^2 A \\ K_{xz} &= (K_p - K_c) \cos A \sin A \\ K_{zz} &= K_p \sin^2 A + K_c \cos^2 A \end{aligned}\right\}. \qquad \text{(B 8)}$$

If the movement is in the direction of the dip, that is, the plus end of the p-axis points down, rotating the orthogonal c-p axes clockwise so that the p-axis lies in the fourth quadrant, by following the same procedure we will obtain the same results for K_{xx} and K_{zz} but

$$K_{xz} = K_{zx} = -(K_p - K_c) \cos A \sin A . \tag{B 9}$$

Equation B 9 is contained in equation B 8, if it is remembered that the angle A is in the first quadrant in equation B 8, but in the fourth quadrant in equation B 9, in which quadrant the sine is negative, although the cosine is positive.

As a practical instance of the application of these results, consider the movement of ground water toward a stream flowing along the geologic strike. The overall movement of the ground water through a large segment of flow will be approximately horizontal. What are the conditions for horizontal flow in the x-direction of our equations even in case the data are too few to determine the vertical gradient?

For purely horizontal flow in the vertical plane containing the dip, q_z must be 0.

$$-q_z = K_{zz}\frac{\partial h}{\partial z} + K_{zx}\frac{\partial h}{\partial x} = 0$$

$$\frac{\partial h}{\partial z} = -\frac{K_{zx}}{K_{zz}}\frac{\partial h}{\partial x} . \tag{B 10}$$

For horizontal flow across inclined beds (other than vertical) of different permeabilities there must always be a vertical gradient. In other words the vertical gradient does not imply a vertical component of movement; it is necessary to maintain horizontal movement across the inclined beds.

We may therefore write

$$-q_x = K_{xx}\frac{\partial h}{\partial x} + K_{xz}\frac{\partial h}{\partial z} ,$$

and from equation B 10,

$$-q_x = \left[K_{xx} - K_{xz}\left(\frac{K_{zx}}{K_{zz}}\right)\right]\frac{\partial h}{\partial x}$$

$$= \frac{K_{xx}K_{zz} - K_{xz}^2}{K_{zz}}\frac{\partial h}{\partial x} \tag{B 11}$$

$$-q_x K_{zz} = (K_{xx}K_{zz} - K_{xz}^2)\frac{\partial h}{\partial x} .$$

Substituting B 8

$$-q_x K_{zz} = [\,(K_p \cos^2 A + K_c \sin^2 A)\,(K_p \sin^2 A + K_c \cos^2 A)$$

$$-(K_p - K_c)^2 \cos^2 A \sin^2 A\,]\frac{\partial h}{\partial x}$$

$$= [K_p^2 \cos^2 A \sin^2 A + K_p K_c \cos^4 A + K_p K_c \sin^4 A + K_c^2 \cos^2 A \sin^2 A$$

$$- (K_p^2 - 2K_p K_c + K_c^2) \cos^2 A \sin^2 A] \frac{\partial h}{\partial x}$$

$$= K_p K_c (\cos^4 A + 2 \cos^2 A \sin^2 A + \sin^4 A) \frac{\partial h}{\partial x}$$

$$= K_p K_c (\cos^2 A + \sin^2 A)^2 \frac{\partial h}{\partial x} = K_p K_c \frac{\partial h}{\partial x}$$

$$-q_x = \frac{K_p K_c}{K_{zz}} \frac{\partial h}{\partial x} \quad \text{(for horizontal flow).} \qquad \text{(B 12)}$$

This equation may be put in more readily used form by writing R for the ratio K_c / K_p, and referring to equations B 8.

$$-q_x = \frac{R K_p K_p \frac{\partial h}{\partial x}}{K_p \sin^2 A + R K_p \cos^2 A}$$

$$= \frac{R}{1 - (1 - R) \cos^2 A} K_p \frac{\partial h}{\partial x} \qquad \text{(B 13)}$$

Figure B-3 gives the values of the factor, N, involving R and A, by which $K_p \frac{\partial h}{\partial x}$ is to be multiplied to obtain the horizontal flux in the plane of the dip. Obviously, this expression is to be used with caution because the vertical gradient may be pronounced. The figure also gives the ratio of the implied vertical gradient to the horizontal gradient. In case the horizontal flow is in the updip direction, the head decreases downward; if the horizontal flow is in the compass direction of the dip, the head increases downward.

It should also be noted that the highest conductivity K_p is along the y-axis. If any permanent tributary streams exist along the dip, ground-water movement will be toward them, and there should be a component of hydraulic gradient along the y-axis indicating this. The development of rectangular drainage typical of the folded Appalachian area in which the stream along the strike commonly has tributaries along the dip direction is probably in large part correlative with this hydraulic situation.

The conductivity coefficients can be depicted graphically by making use of the 2,000-year-old observation that $\cos 2A = 2 \cos^2 A - 1 = 1 - 2 \sin^2 A$ and $\sin 2A = 2 \sin A \cos A$. Transforming equations B 8, we have

$$\left.\begin{aligned} K_{xx} &= [(K_p + K_c) + (K_p - K_c) \cos 2A]/2 \\ K_{xz} = K_{zx} &= [(K_p - K_c) \sin 2A]/2 \\ K_{zz} &= [(K_p + K_c) - (K_p - K_c) \cos 2A]/2 \end{aligned}\right\} . \qquad \text{(B 14)}$$

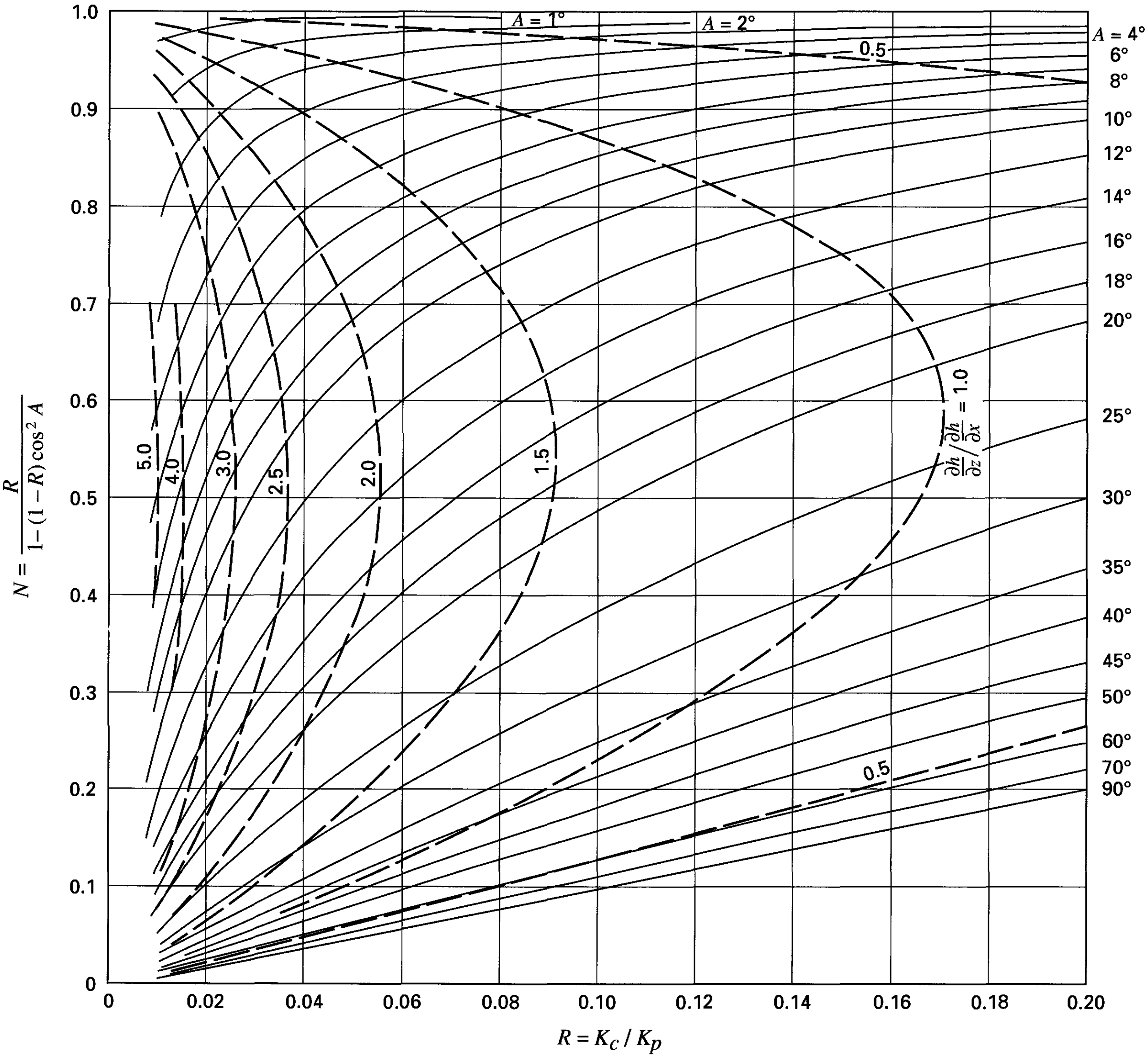


Figure B-3. Value of factor N in equation for horizontal flow across inclined bedding, $-q_x = NK_p \frac{\partial h}{\partial x}$, and for the ratio, $\frac{\partial h}{\partial z} / \frac{\partial h}{\partial x}$, for various angles of dip and ratios of conductivity.

A Mohr's circle can be constructed to show these relations (Bear and others, 1968; Nye, 1957, p. 43), as shown in figure B-4. The values of K_c and K_p are laid off on a straight line. A circle is drawn with its center on this line and passing through the points for K_c and K_p. The angle 2A is drawn within this circle. The values of the conductivity coefficients have then the values shown in the figure as can be easily verified by a comparison of the equations. Such a diagram is particularly useful in visualizing the change in the coefficients as the angle of dip changes or as the relative values of K_p and K_c change.

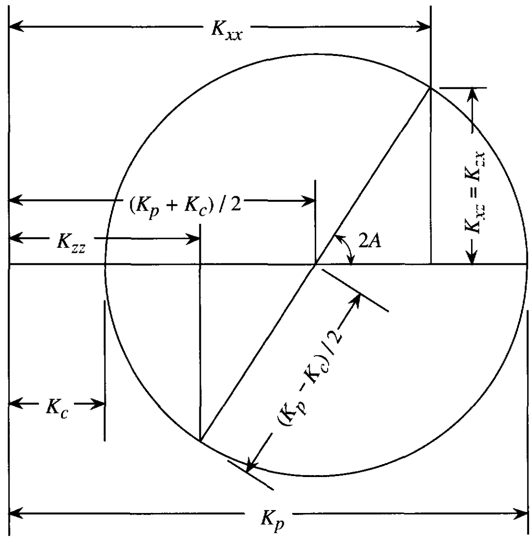


Figure B-4. Mohr's circle giving conductivity coefficients for dipping beds.

C. THE GENERAL EQUATIONS FOR CONDUCTIVITY COEFFICIENTS

When dealing with dipping beds, lineation features may exist in the plane of the bedding so that there may be two different conductivity axes in the bedding plane. In general, these axes would be at some angle to the strike of the beds.

The procedure for treating this condition is no different in principle from that used in the more simple case just considered of beds that are uniform in permeability in the bedding plane. We project the components of hydraulic gradient along the coordinate axes *x*, *y*, *z*, onto the conductivity axes, obtain the fluxes on these axes, and finally project the fluxes back on the coordinate axes. The only difference is that we have nine combinations of axes to consider.

Analogously to equations B 6, we write

$$\left.\begin{aligned} -q_x &= K_{xx}\frac{\partial h}{\partial x} + K_{xy}\frac{\partial h}{\partial y} + K_{xz}\frac{\partial h}{\partial z} \\ -q_y &= K_{yx}\frac{\partial h}{\partial x} + K_{yy}\frac{\partial h}{\partial y} + K_{yz}\frac{\partial h}{\partial z} \\ -q_z &= K_{zx}\frac{\partial h}{\partial x} + K_{zy}\frac{\partial h}{\partial y} + K_{zz}\frac{\partial h}{\partial z} \end{aligned}\right\} . \qquad \text{(C 1)}$$

The *K*'s in C 1 are the components of the *conductivity tensor.*

If we designate the conductivity axes as *1, 2, 3* and the principal conductivities as K_1, K_2, K_3, respectively, we have as an extension of equations B 7

$$\left.\begin{aligned}
K_{xx} &= K_1 \cos^2(x1) + K_2 \cos^2(x2) + K_3 \cos^2(x3) \\
K_{xy} &= K_1 \cos(x1)\cos(y1) + K_2 \cos(x2)\cos(y2) + K_3 \cos(x3)\cos(y3) \\
K_{xz} &= K_1 \cos(x1)\cos(z1) + K_2 \cos(x2)\cos(z2) + K_3 \cos(x3)\cos(z3) \\
K_{yx} &= K_1 \cos(y1)\cos(x1) + K_2 \cos(y2)\cos(x2) + K_3 \cos(y3)\cos(x3) = K_{xy} \\
K_{yy} &= K_1 \cos^2(y1) + K_2 \cos^2(y2) + K_3 \cos^2(y3) \\
K_{yz} &= K_1 \cos(y1)\cos(z1) + K_2 \cos(y2)\cos(z2) + K_3 \cos(y3)\cos(z3) \\
K_{zx} &= K_{xz} \\
K_{zy} &= K_{yz} \\
K_{zz} &= K_1 \cos^2(z1) + K_2 \cos^2(z2) + K_3 \cos^2(z3)
\end{aligned}\right\} . \qquad \text{(C 2)}$$

Because the nine different conductivity coefficients are reduced to six different values, that is, the two subscripts can be transposed without changing the value, the conductivity tensor is *symmetric.*

These nine coefficients can be expressed concisely as

$$K_{mn} = \sum_{i=1}^{3} K_i \cos(mi)\cos(ni) \qquad \text{(C 3)}$$

in which *m* and *n* each takes successively the terms *x, y,* and *z*. It may be observed that $-K_i \cos(ni)\frac{\partial h}{\partial n}$ represents the flow component along the conductivity axis *i* due to the head gradient on the axis *n*, and that multiplication by cos (*mi*) gives the component of that flow on the coordinate axis *m.*

This is a general expression for the hydraulic conductivity under any conditions of isotropy or anisotropy. For instance, if the conductivity axes *1, 2,* and *3* are collinear with the *x, y,* and *z* axes respectively, the cosines of the angles will be as follows:

Conductivity axis		***1***	***2***	***3***
	x	1	0	0
Coordinate axis	*y*	0	1	0
	z	0	0	1

and the values for q become

$$-q_x = K_1 \frac{\partial h}{\partial x}$$

$$-q_y = K_2 \frac{\partial h}{\partial y}$$

$$-q_z = K_3 \frac{\partial h}{\partial z}$$

which is the case considered in Section A.

If further, $K_1 = K_2 = K_3 = K$, the isotropic model is obtained.

The most general model for conductivity is likely to be most useful in the case of dipping sediments in which some lineation pattern might be known or suspected in the plane of the bedding giving rise to conductivity axes in the bedding plane which in general would be at some angle to the strike of the beds. The most feasible procedure is to aline the x- and z-axes in the plane of the dip. The angle of dip will be designated A as before, and the angle that one of the bedding-plane axes makes with the strike direction will be called B.

The relation of the two sets of axes is best shown on a stereographic projection. In this projection the two sets of axes are projected to their intersections with a sphere of unit radius. The axes are represented by these points on the unit sphere, and the arcs of the great circles connecting pairs of points measure the angles between axes. The stereographic projection is made by connecting those points with the opposite poles ($\pm z$) of the sphere by straight lines. The points of intersection of these lines with the xy-plane form the stereographic projection. One of the characteristics of the stereographic projection is that arcs of great (or small) circles on the sphere are also arcs of circles on the projection. Figure C-1 is such a projection.

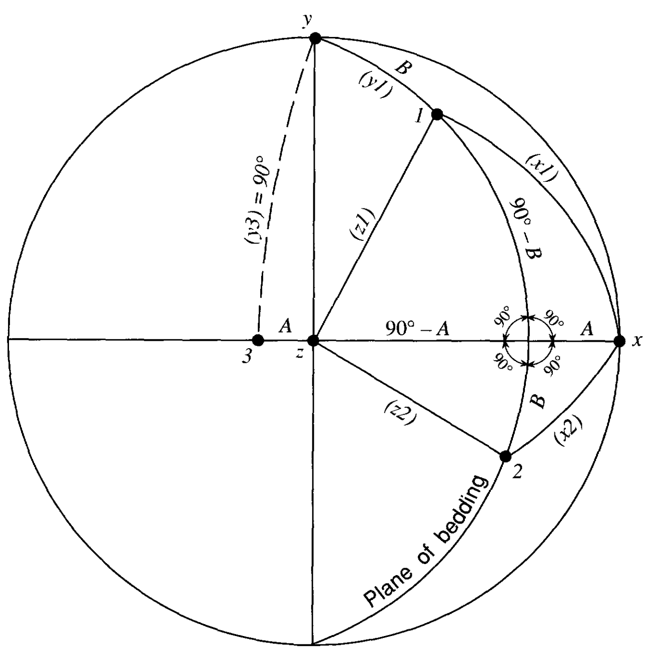


Figure C-1. Stereographic projection showing the relations of the conductivity and coordinate axes.

The various angles of interest (arcs or radii in the projection) are parts of right spherical triangles on the sphere. In such triangles the cosine of the hypotenuse is equal to the product of the cosines of the other two sides. We can therefore write the cosines of the angles between axes directly from the projection.

$$\cos(x1) = \cos(90° - B)\ \cos A = \sin B\ \cos A$$
$$\cos(x2) = \cos B\ \cos A$$
$$\cos(x3) = \cos(90° + A) = -\sin A$$
$$\cos(y1) = \cos B$$
$$\cos(y2) = \cos(90° + B) = -\sin B$$
$$\cos(y3) = \cos 90° = 0$$
$$\cos(z1) = \cos(90° - B)\ \cos(90° - A) = \sin B\ \sin A$$
$$\cos(z2) = \cos B\ \cos(90° - A) = \cos B\ \sin A$$
$$\cos(z3) = \cos A$$

Substituting these values into equations C 2, we can therefore write the conductivity coefficients

$$K_{xx} = K_1 \sin^2 B \cos^2 A + K_2 \cos^2 B \cos^2 A + K_3 \sin^2 A$$
$$= (K_1 \sin^2 B + K_2 \cos^2 B) \cos^2 A + K_3 \sin^2 A$$
$$= (K_1 \sin^2 B + K_2 \cos^2 B - K_3) \cos^2 A + K_3$$
$$K_{xy} = K_1 \sin B \cos B \cos A - K_2 \sin B \cos B \cos A + 0$$
$$= (K_1 - K_2) \sin B \cos B \cos A$$
$$K_{xz} = K_1 \sin^2 B \sin A \cos A + K_2 \cos^2 B \sin A \cos A - K_3 \sin A \cos A$$
$$= (K_1 \sin^2 B + K_2 \cos^2 B - K_3) \sin A \cos A$$
$$K_{yx} = K_{xy}$$
$$K_{yy} = K_1 \cos^2 B + K_2 \sin^2 B + 0$$
$$K_{yz} = K_1 \sin B \cos B \sin A - K_2 \sin B \cos B \sin A + 0$$
$$= (K_1 - K_2) \sin B \cos B \sin A$$
$$K_{zx} = K_{xz}$$
$$K_{zy} = K_{yz}$$
$$K_{zz} = K_1 \sin^2 B \sin^2 A + K_2 \cos^2 B \sin^2 A + K_3 \cos^2 A$$
$$= (K_1 \sin^2 B + K_2 \cos^2 B - K_3) \sin^2 A + K_3$$

It may be noted that K_{xx}, K_{xz}, and K_{zz} contain the same term involving B as do also K_{xy} and K_{yz}. These equations are for movement against the dip; the angle A lies in the first quadrant. For movement in the compass direction of the dip, the angle A lies in the fourth quadrant and the sine is negative; hence, K_{xz}, K_{yz}, K_{zx}, and K_{zy} are negative.

The preceding equations involve, in general, a function of B, $F(B)$, multiplied by a function of A, $F(A)$, with modifications involving K_3 for K_{xx}, K_{xz}, and K_{zz}.

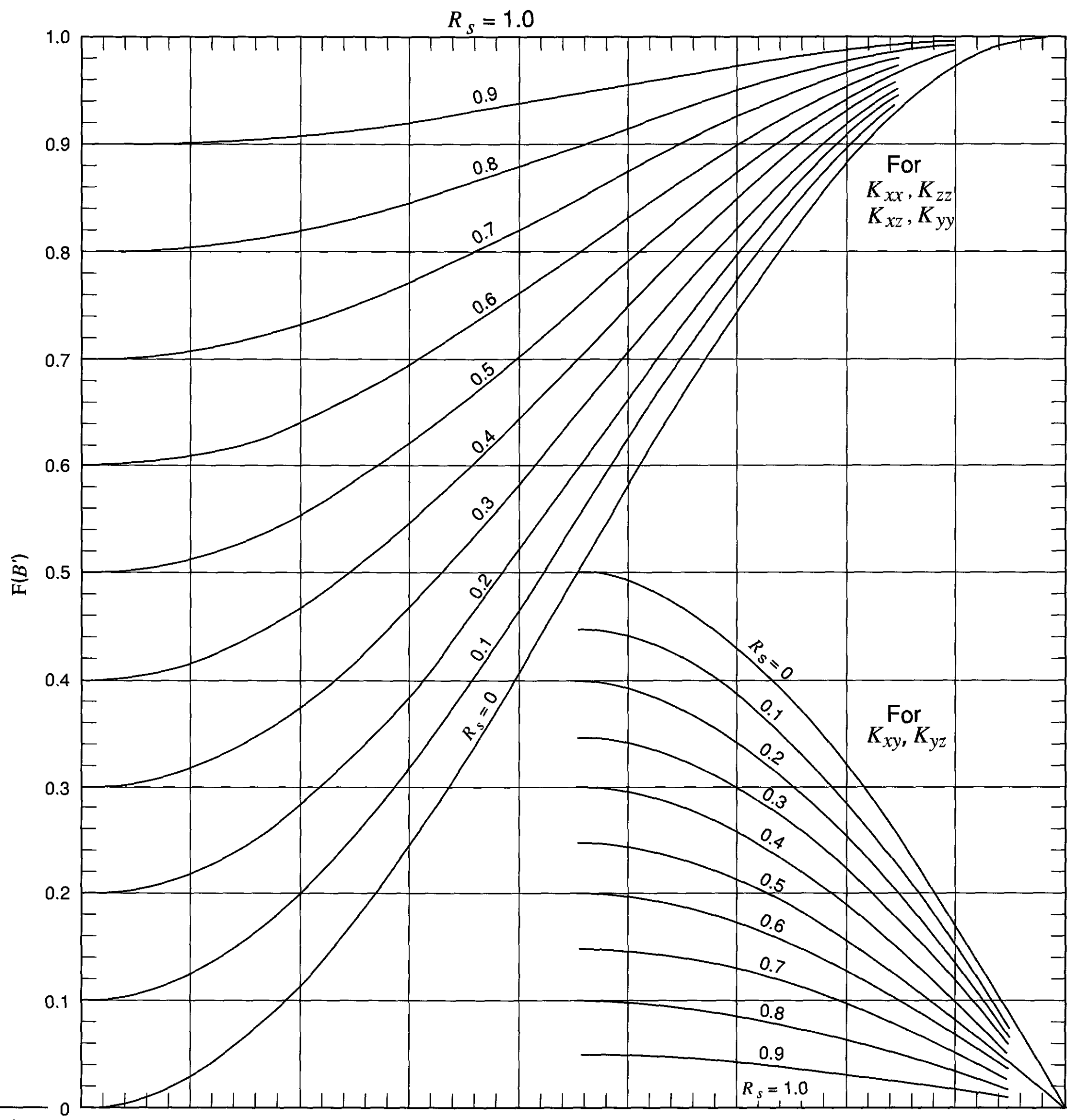
Figure C-2 is a diagram giving $F(B)$, except for the modification needed for K_3. For the purpose of the diagram, we define the angle B' as the angle between the y-axis and the axis of greater bedding-plane conductivity, K_g, which may be either axis *1* or axis *2*. Hence $B' = B$ or $B + 90°$. The other, smaller, conductivity will be designated as K_s. We shall further define $R_s = K_s / K_g$, and $R_c = K_c / K_g$. By making appropriate use of the relation $\sin^2 B + \cos^2 B = 1$, and dividing the conductivity coefficients by K_g we can write

	$B' = B$	$B' = B + 90°$
$\frac{K_{xx}}{K_g} =$	$\left[(1-R_s)\sin^2 B + R_s - R_c\right]\cos^2 A + R_c$	$\left[(1-R_s)\cos^2 B + R_s - R_c\right]\cos^2 A + R_c$
$\frac{K_{xy}}{K_g} =$	$[(1-R_s)\sin B \cos B]\cos A$	$[-(1-R_s)\sin B \cos B]\cos A$
$\frac{K_{xz}}{K_g} =$	$\left[(1-R_s)\sin^2 B + R_s - R_c\right]\sin A \cos A$	$\left[(1-R_s)\cos^2 B + R_s - R_c\right]\sin A \cos A$
$\frac{K_{yy}}{K_g} =$	$\left[(1-R_s)\cos^2 B + R_s\right]\times 1$	$\left[(1-R_s)\sin^2 B + R_s\right]\times 1$
$\frac{K_{yz}}{K_g} =$	$[(1-R_s)\sin B \cos B]\sin A$	$[-(1-R_s)\sin B \cos B]\sin A$
$\frac{K_{zz}}{K_g} =$	$\left[(1-R_s)\sin^2 B + R_s - R_c\right]\sin^2 A + R_c$	$\left[(1-R_s)\cos^2 B + R_s - R_c\right]\sin^2 A + R_c$

These equations include only two basic functions of B. The main diagram in figure C-2 is the system of curves $F(B') = (1-R_s)\sin^2 B + R_s$. Inasmuch as $\cos^2 B = \sin^2(90°+B) = \sin^2(90°-B)$, it is only necessary to read the B' scale backwards to obtain the $\cos^2$ function. To obtain K_{xx} / K_g, K_{xz} / K_g, and K_{zz} / K_g, R_c must be subtracted from the values given on the diagram before multiplying by $F(A)$ and for K_{xx} / K_g and K_{zz} / K_g, R_c should be added in again after multiplying. For conductivity coefficients involving the y-axis, R_c is not involved.

The second function appearing is $(1-R_s)\sin B \cos B$ and is given in the lower right part of the chart. This has a maximum value of 0.5 for $B' = 45°$ and is symmetrical around the 45° axis. When $B' > 90°$, the $F(B')$ values are negative but equal in absolute value to those for $B' < 90°$.

It may be interesting to note that for $R_s = 1$, the values for the various coefficients degenerate into the coefficients used in Section B, and for $A = 0°$ or $90°$, $B = 0°$ or $90°$, they give the coefficients used in Section A.



	F(A)	B'									
K_{xx}/K_g	$\cos^2 A$	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
K_{zz}/K_g	$\sin^2 A$	180°	170°	160°	150°	140°	130°	120°	110°	100°	90°
K_{xz}/K_g	$\sin A \cos A$	Subtract R_c from values given to obtain F(B'); For K_{xx} and K_{zz} add R_c after multilpying by F(A)									
K_{yy}/K_g	1	90° 90°	80° 100°	70° 110°	60° 120°	50° 130°	40° 140°	30° 150°	20° 160°	10° 170°	0° 180°
K_{xy}/K_g	$\cos A$	F(B') for K_{xy}, K_{yz} is positive				45°	40° 50°	30° 60°	20° 70°	10° 80°	0° 90°
K_{yz}/K_g	$\sin A$	F(B') for K_{xy}, K_{yz} is negative				135°	130° 140°	120° 150°	110° 160°	100° 170°	90° 180°
	For movement against dip F(A) always positive. For movement with dip, $\sin A$ is negative; hence, F(A) for K_{xz} and K_{yz} is negative										

Figure C-2. Function of B' used in obtaining conductivity coefficients. See text for explanation.

SELECTED ANNOTATED BIBLIOGRAPHY

For those more proficient in the mathematical treatment of tensors than has been assumed in the foregoing pages, a few texts, among many, may be cited.

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A complete and thorough treatment of all phases of ground-water movement, tersely written. The reader should understand "the principles of vector analysis, partial differential equations, elements of the theory of functions and conformal mapping, some hydrodynamics and thermodynamics."

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Comments on "A Primer on Anisotropy" by C.V. Theis and on Related Notes from Theis' Files

By **Charles A. Appel**

INTRODUCTION

These comments are the result of intensive review of C.V. Theis' 1971 and 1974 drafts of "A Primer on Anisotropy," careful study of correspondence between Theis and several reviewers of the early drafts of the manuscript, and scrutiny of relevant literature that was available to Theis at the time and that was published subsequently. The comments also include the results of review of notes from Theis' files that apparently represent his efforts to expand the primer. Opinions of some of the hydrologists who reviewed the primer in 1990 are incorporated as well.

All terms and symbols used in these comments are as they were defined in the Theis primer. All references to lettered sections, designated equations, for example, A 1, A 2, B 1, B 2, etc.; and to figures, A-1, A-2, etc., are to those presented in the primer.

Critical review of these comments by Alfred Clebsch, G.A. Hearne, T.E. Reilly, John Vecchioli, and E.P. Weeks is gratefully acknowledged, as is the discussion (see section "Recent Reviews of the Primer") by Paul A. Hsieh of Theis' explanation for the symmetry of the hydraulic-conductivity tensor. Their suggestions resulted in improvement of the content and clarity of the comments.

BACKGROUND ON THE DEVELOPMENT OF THE PRIMER

From the late 1940's and into the 1960's, C.V. Theis was interested in problems of mass transport of contaminants in ground water as a result of his work with the U.S. Atomic Energy Commission on radioactive waste disposal. He became increasingly concerned with the inadequacies of flow models that were based on the assumption of homogeneous, isotropic distribution of aquifer characteristics in attempting to understand and predict the flow paths and concentration distribution of contaminants. This concern, plus his participation in a committee effort to redefine ground-water terminology and concepts (Lohman and others, 1972), and his involvement in training courses for ground-water hydrologists of the U.S. Geological Survey served as a foundation for writing the primer (a small introductory book on a specific subject).

The beginnings and early chronology of the primer are unclear, but notes by Theis bearing a 1964 date, prepared apparently as part of the course in ground water that he taught at Columbia University, indicate that he had already given considerable thought to the subject and had begun analyzing the problem mathematically. By February 1971, work on it had progressed to the point that a draft was sent to several U.S. Geological Survey colleagues for review, asking " * * * if you think it would be of any use? Is anything wrong? Or anything that needs adding?"

Theis revised the 1971 draft in response to reviewers' suggestions and resubmitted the revision for additional review by some of the same reviewers and some additional ones. Revisions of this intermediate draft culminated in a version dated May 1974 that is essentially the same as the one published in this Water-Supply Paper. It includes minor editorial changes; some were made subsequently by Theis and others were made in preparation for this publication.

The contributions of Theis to the development of the quantitative concepts and methodologies in groundwater hydrology are well known. Some of the best known of those contributions extended the understanding of ground water through the development of new functional relations. The Theis manuscript made no claim of presenting new, previously unknown results but was intended instead to present "* * * a treatment of anisotropy from a rather elementary standpoint * * *."

Theis never submitted the manuscript for publication, although the fact that he had the illustrations drafted to publication standards suggests that he intended to do so. Some notes from Theis' files hint of material that he may have considered adding to the primer, perhaps in response to reviewers' suggestions. It may be that a multitude of ideas occurred to him for extensions of sections or for additional subjects to include in the paper, which, in turn, created a dilemma and an effective deterrent; the more complete the coverage of different aspects of anisotropy, the less like a primer it would be. Notwithstanding these uncertainties and potential deficiencies, the primer reveals Theis' insight into this difficult aspect of ground-water hydrology and presents the subject with notable thoroughness and clarity.

In asking Hilton H. Cooper to review the February 1971 draft of the primer, which Theis referred to as the "Joe Doakes' Primer on Anisotropy," Theis noted that "* * * I hope you will do this because you were responsible for my writing it. Do you remember that when we were defining terms, I suggested you explain conductivity coefficients to Joe Doakes and you didn't want to do it?" (The reference to Joe Doakes is to the potential user, the average man.) By the statement "when we were defining terms," Theis must have been referring to Cooper's and his participation in an ad hoc Committee on Redefinition of Ground-Water Terms, formed October 21, 1965, in the Water Resources Division of the U.S. Geological Survey. That committee prepared a report (Lohman and others, 1972) that revised, refined, and redefined a number of ground-water terms. An especially important aspect was the relating of terminology to the mathematics of ground-water flow. In that report (p. 4 and 5), the definition of *hydraulic conductivity* includes a discussion of anisotropic conditions that indicates that, in anisotropic media, the direction of the specific discharge is not generally parallel to the direction of the gradient of the head; and that, in such media, the Cartesian components of the specific discharge are related to those of the gradient by an equation identical to that designated in Theis' primer as equation C 1. The committee report goes on to describe, in words, the physical significance of the directional hydraulic-conductivity coefficients of the form K_{xx}, K_{xy}, K_{xz}, and so forth.

The format of the Lohman and others (1972) report did not include the use of diagrams to aid in conveying ideas, terms, or concepts. Theis used diagrams (see Theis' figures B-1 and B-2) effectively to develop an understanding of the equations relating the Cartesian components of the specific discharge to the components of the hydraulic gradient. He shows, for example, how the components of the hydraulic gradient on a selected (say *xz*) coordinate system are used to form components of flow on the axes that correspond to the principal directions of hydraulic conductivity, and those flow components, in turn, can be projected back onto the *xz* axes and summed (vectorially) to determine components of flow in the *xz* plane. Theis apparently judged that the discussion on anisotropy in Lohman and others (1972) and the discussions in that part of the literature on anisotropy with which he was familiar were not sufficiently elementary to be fully understood by many readers—thus, the reference to the primer being intended for "Joe Doakes." Clearly, an answer to "why did Theis prepare this paper?" was to try to explain anisotropy in a more understandable way to the practicing hydrogeologist.

Theis' files indicate that Hilton Cooper reviewed at least the 1971 draft and one later version of the primer. Theis and Cooper exchanged several memos on the manuscript and on the general subject of anisotropic flow systems. In a memo to Theis dated March 15, 1971, Cooper stated:

> My review of your paper on anisotropy caused me to do some reading on crystallography, a subject that I have known little about. This led me to a discovery of one of the clearest and most complete books on tensors and anisotropy that I have ever seen. It is, "Physical properties of crystals, their representation by tensors and matrices," by J.F. Nye, published by Oxford at the Clarendon Press, 1957. Much of the subject is, of course, applicable to ground-water flow. I was delighted with your primer and am looking forward to seeing the final product.

Theis' annotated bibliography for the paper includes the Nye reference.

Theis had a thorough knowledge of crystallography, having taught the subject as a graduate assistant at the University of Cincinnati in the 1920's, and he was familiar with the use of stereographic projections in both crystallography and structural geology. Theis used a stereographic projection (fig. C-1) to show the relations of the hydraulic-conductivity and the coordinate axes.

A memo from Cooper to Theis, dated December 13, 1971, conveying some review comments and a manuscript, starts:

> I have reviewed your paper on anisotropy and feel that it will answer a long-standing need. I know that there are many hydrologists, including the bachelor engineers of my day, who are good at math but do not have a good understanding of the equations of ground-water flow in anisotropic media because they lack a background in tensors. You have successfully developed these equations without the use of tensors.
>
> The math in your paper will be far from easy reading, even for those skilled in vectors, trigonometry, and differential equations, and, like Stan [Stanley W. Lohman], I wonder whether "primer" is appropriate. I have no firm opinion on this, but you might consider some other title that would get across the idea you have in mind. Maybe "Anisotropy without tensors" would not be too bad.

In preparation for this publication, and indeed to decide whether to publish the primer, the manuscript was reviewed again in 1990. As might be expected after almost two decades of progress in ground-water hydrology, these later reviews were less enthusiastic than those of the 1970's; one of the more significant comments is summarized in the section, "Recent Reviews of the Primer."

Although Theis did not submit the manuscript for publication, he did share its contents with colleagues. Theis gave a few days' training workshop on anisotropy to the staff in the New Mexico Water Resources Division office of the U.S. Geological Survey in December 1974. The May 1974 version of the paper was used in that workshop. Theis, and others, also gave several 1-hour presentations on anisotropy based on the primer at U.S. Geological Survey ground-water training courses held in the early and mid-1970's. On a less formal level, he discussed the applicability of the anisotropic formulation to real field problems with colleagues. Reports by Koopman (1975) and Hearne (1985a, b) include applications of some of Theis' results for field problems in New Mexico where flow through dipping sequences of fine- and coarse-grained sediments was apparently horizontal.

APPLICATIONS OF THE PRIMER

Besides trying to explain anisotropy more clearly than he believed had been done before, Theis was trying to put some of the potentially useful results in a more readily usable form by preparing nomographs. Hearne (1985b, p. 9) applied Theis' results, including the nomograph (fig. B-3 in the primer) to analyze apparently horizontal flow under unstressed conditions through a section of the Tesuque aquifer system to make preliminary estimates of its anisotropy ratio. The Tesuque aquifer system consists of interbedded gravel, sand, silt, and clay with some intercalated beds of volcanic ash. Individual clastic beds are probably not continuous throughout the basin, and faults further disrupt the continuity of the beds. Flow is from the front of the Sangre de Cristo Mountains on the east—the major recharge area—through the Tesuque aquifer system to the Rio Grande on the west—the discharge area. Flow was assumed to be nearly horizontal at the site of interest. The horizontal component of the hydraulic gradient $(\partial h/\partial x)$ was estimated from contours of the head surface to be about 0.02. On the basis of measurements of piezometers emplaced in different sandy beds between altitudes of 5,650 and 6,200 feet, the vertical component of the hydraulic gradient $(\partial h/\partial z)$ was estimated to be about 0.12. Thus, the ratio of the vertical to the horizontal components of the hydraulic gradient is

$$\frac{\partial h/\partial z}{\partial h/\partial x} = \frac{0.12}{0.02} = 6.$$

The beds of the Tesuque aquifer system dip toward the Rio Grande at about 7 degrees.

In figure B-3, the largest value of $\dfrac{\partial h/\partial z}{\partial h/\partial x}$ shown is the 5.0 curve, and its intersection with the curve, corresponding to an angle of dip A of 7 degrees, has a value of $R = K_c / K_p$ of about 0.01, where R is the ratio obtained by dividing the hydraulic conductivity perpendicular to the bedding by the hydraulic conductivity parallel to the bedding. A value of $\dfrac{\partial h/\partial z}{\partial h/\partial x}$ larger than 5.0 would be farther yet to the left, and because of the shape of the curves in this part of the graph, $R = K_c / K_p$ is less than 0.01 for a value of $\frac{\partial h/\partial z}{\partial h/\partial x} = 6.0$. To supplement Theis' figure B-3, note that the relation used to compute values of K_c / K_p can be obtained from equations B 10 for strictly horizontal flow, written using expressions for K_{zz} and K_{zx} from equations B 8 and B 9, gives (Hearne, 1985b):

$$\frac{K_c}{K_p} = \frac{\sin A\,(\cos A \frac{\partial h}{\partial x} + \sin A \frac{\partial h}{\partial z})}{\cos A\,(\sin A \frac{\partial h}{\partial x} - \cos A \frac{\partial h}{\partial z})}$$

where A is the angle of dip of the bedding (negative for downdip flow). Using this equation, for $A = -7$ degrees and $\frac{\partial h/\partial z}{\partial h/\partial x} = 6.0$, K_c / K_p is computed to be 0.005; therefore, the anisotropy ratio is significant. On the basis of estimates of this type, a digital model that was developed for the Tesuque aquifer system (Hearne, 1985a, b) was designed to orient the layers of grid blocks in the direction of the dip of the aquifer system to make the principal direction of the hydraulic conductivities of the aquifer system correspond to the coordinate system used.

Hearne (1985a, p. 44) noted that, for horizontal flow across dipping anisotropic beds, it may be convenient to recognize that Theis' equation B 13 indicates an effective horizontal anisotropy in which

$$\frac{K_x}{K_y} = \frac{R}{1 - (1 - R)\cos^2 A}$$

where K_x is the horizontal hydraulic conductivity in the direction of the dip (*L/T*); and K_y (equivalent to Theis' K_p in his section B) is the horizontal hydraulic conductivity in the direction of the strike (*L/T*), and R and A are defined as before.

The other nomograph in the primer, figure C-2, is an aid in determining the hydraulic-conductivity coefficients, given a set of orthogonal coordinate axes and the principal hydraulic-conductivity values and their directions. The assumption is made in section C that there may be two different principal hydraulic-conductivity axes in the bedding plane, which, in general, are at some angle to the strike of the bed. As in section B, the assumption is made in section C that a principal hydraulic-conductivity axis is perpendicular to the bedding.

There is a fundamental difference between figures B-3 and C-2. Figure B-3 is useful because it helps to visualize the relation between the dip angle, A, the ratio

$$\frac{\partial h/\partial z}{\partial h/\partial x}$$

and the anisotropic ratio K_c / K_p. In contrast, figure C-2 shows the relation between the angle B' (angle between strike and direction of greater principal hydraulic-conductivity axis in the bedding plane); the ratio $R_s = K_s / K_g$; the term $F(B') = (1-R_s)\sin^2 B + R_s$; and the term $(1-R_s)\sin B \cos B$. These expressions are of interest because they are related to hydraulic-conductivity coefficients. But the relations shown by figure C-2 are only part of the total relation. In some cases, the total relation involves subtracting from $F(B')$ the term K_c / K_g; then multiplying the result by $\sin^2 A$ or $\cos^2 A$, depending on which conductivity coefficient is being calculated, and then adding K_c / K_g to that result.

UNANSWERED QUESTIONS ABOUT THE PRIMER

Why did Theis not submit the primer for publication? Why did he not add examples? What is the significance of the notes from the Theis file, labeled Anisotropy, which contained drafts, calculations, notes, review comments, and correspondence with reviewers?

Several reviewers in the 1970's encouraged Theis to publish the paper. A statement in one of Theis' letters indicates that at least one person had recommended that some example problems and their solutions be added to the primer. Material found in Theis' files suggests that he considered adding some examples, but coworkers and associates at the time now recall that Theis was reluctant to add examples because of the time it would take. Another possible contributing factor may have been additional topics that Theis considered adding but did not complete. Some of these possibilities are discussed in the following paragraphs.

In Theis' February 18, 1971, memorandum transmitting the manuscript to Hilton Cooper for review, he indicated that he wanted

> * * * to add two more sections to this opus. The first is to show the distortion in the *xy* plane of the right angle between two conductivity axes in the plane of the bedding and also to give the conductivity coefficient when the dip of the beds and the angle within the bedding of these axes is known. The second is to indicate when alined alternating low and high permeability beds may be considered a homogeneous, anisotropic mass, that is, the old idea that homogeneity is a function of scale.

Undated handwritten material in Theis' files indicates two approaches to a possible section on relating steady state linear flow through two homogeneous and isotropic layers and an equivalent homogeneous and anisotropic zone of equal thickness. Here "equivalent" is taken to mean that, given the same hydraulic heads at the boundaries of the two flow systems—one real and the other imaginary, the flow through the real two-layer system will be the same as the flow through the imaginary single-layer anisotropic system.

Theis' primer made clear that, in many cases, the property of hydraulic anisotropy results from an "* * * alinement of nonhomogeneous features * * * and that these * * * may be treated as an anisotropic condition when the scale of the problem studied is such that a considerable number of such similarly oriented, elongated nonhomogeneities are included." The use of "scale" and "a considerable number of such similarly oriented" involve some ideas that are worthy of an expanded comment. Theis apparently assumed that the reader was familiar with the formulas to compute the equivalent hydraulic conductivity parallel to individually homogeneous and isotropic beds of different thicknesses and hydraulic conductivities. He also assumed that the reader could compute the equivalent hydraulic conductivity for flow perpendicular to such beds. If the rocks or soils comprising such beds function as an equivalent homogeneous anisotropic medium, then there are some constraints on the thicknesses and properties of the homogeneous and isotropic beds. This approach was not new. In a discussion on "A layered medium as an equivalent anisotropic medium," Bear (1972, p. 155-157) credited Vreedenburgh (1937) as the first to develop a relation between the equivalent hydraulic conductivity for flow in a specified direction relative to the bedding and the equivalent hydraulic conductivities parallel to and perpendicular to the bedding—for a two-layer system. Bear (1972) credited Marcus and Evenson (1961) for a generalization of the two-layered system to an n-layered system; also see Marcus (1962).

Notes in Theis' files indicate that he considered the generalization of flow in a specified direction through parallel beds, where each bed is homogeneous and anisotropic. Specifically, he considered flow through a system made up of one thin, relatively permeable anisotropic bed and one thick, poorly permeable anisotropic bed; he also considered flow through an equivalent single, homogeneous anisotropic bed.

Handwritten notes in Theis' files also include the mathematical development for strictly horizontal flow (that is, $q_z = 0$) where there are two conductivity axes that have different values of conductivity in the bedding plane, and neither axis is the direction of the strike. Such a situation is a generalization of section B, equations B 10 to B 13, and most appropriately would have been added to section C of the primer.

Theis' notes include other material that also could be part of an extension and generalization of section B of the primer. Handwritten notes cover the case where it is assumed that the water table slopes and that "* * *the movement of the water just beneath the water table will be parallel to it and there will be in consequence a component of movement in the vertical direction* * *" (quotation from Theis' notes). The mathematical development parallels the development in section B between equations B 10 and B 13.

LIMITATIONS ON THE TRANSFORMATION OF ANISOTROPIC AQUIFERS INTO EQUIVALENT ISOTROPIC AQUIFERS

Besides the unfinished sections that Theis stated that he wanted to add to the primer and others mentioned in the preceding section that he apparently considered, he also gave thought to some of the problems associated with transforming the real dipping anisotropic aquifers into imaginary equivalent isotropic aquifer systems, where presumably a solution would be easier to develop, and then transforming that solution back into the real anisotropic aquifer. For example, see the 2-dimensional case in section A (note fig. A-1), which Theis used to illustrate how a horizontal anisotropic aquifer system involving a well near a river could be transformed to an equivalent isotropic aquifer system. It was natural for Theis to investigate the extent to which such transformations could be used to advantage for other anisotropic flow problems.

In a memorandum to Cooper, dated February 2, 1972, thanking him for his "careful review of my 'Primer'," Theis asked if Cooper had given any thought to some of the problems associated with transforming dipping anisotropic aquifers to equivalent isotropic aquifers for solving the flow equation. As an example, Theis described a field situation where the aquifer has a 25/1 ratio of hydraulic conductivities parallel and perpendicular to the bedding, and the bedded sediments dip about 10 degrees. For a horizontal water table, Theis computed that a well in such a real anisotropic aquifer system corresponds to a well in the transformed equivalent isotropic aquifer system that would make an angle of almost 50 degrees to the water table; whereas, in the real anisotropic aquifer system, the angle between a vertical well and a horizontal water table would be 90 degrees. Theis also noted that for another aquifer system, where the ratio of hydraulic conductivities is about 100/1 and the dip of the bedding is about 30 degrees, the angle between the well and the water table in the transformed equivalent isotropic aquifer system would be almost 13 degrees. Most analytical solutions available for problems involving a well assume that the well is vertical and the upper and lower surfaces of the aquifer are horizontal. For large ratios of anisotropy, the deviation from the vertical of a well in the transformed equivalent isotropic aquifer system gets so large—as illustrated by the two examples cited by Theis—that it may be necessary to account for the effect of that deviation. Theis speculated on some alternative approaches and stated that

> * * * I suppose we might go to some liquid or other 3-dimensional analogue, but I suspect we would forget about transformed space and try to build the tilted anisotropy into a model. Or perhaps drive some digital programmer crazy with the multiplicity of boundary conditions to be met.

A handwritten copy of the following paragraph was found in Theis' files that may suggest what he might have written in an expanded primer.

> It may be observed that analogously to the treatment in part A [section A], space can be transformed along the mutually perpendicular conductivity axes. However, in doing so, all the hydraulic features associated with the horizontal and vertical directions, such as vertical wells, the direction of gravitational force, and the inclination of its water table, must also be transformed into the other coordinates. The result is a system of such complication that no simple solution is possible and a 3-dimensional numerical or analogue model would probably be necessary for the solution.

For boundaries having certain spatial configurations, such transformations may create a more complex geometry. For example, a circular well bore inside a circularly shaped aquifer transforms to an elliptical well bore inside an elliptically shaped aquifer.

In a memorandum to Theis, dated March 30, 1972, Cooper stated:

> You are certainly right about the difficulty of treating a problem of vertical wells in tilted anisotropic beds by rotating the coordinate axes. My attention in my last letter was on the problem of terminology, and I didn't give much thought to the complexities that might arise.

A few years after this exchange of memorandums between Theis and Cooper, a paper by Cinco, Miller, and Ramey (1975) presented results for transient head changes in response to producing (pumping or flowing) from a slanted well in an anisotropic aquifer (conductivities parallel to the bedding are uniform in all directions and may be different from the crossbed conductivity). Although Cinco, Miller, and Ramey (1975) provided an analytical solution for the pressure at any point in the aquifer in response to a partially penetrating slanting production well, the numerical tabulations and graphs of the analytical solution given in the paper that would be useful for practical applications are for conditions only at the fully penetrating producing well itself and not elsewhere in the reservoir. This limited result supports Theis' appraisal of the difficulty of the slanted well problem.

RECENT REVIEWS OF THE PRIMER

Recent reviews of the primer raised questions about Theis' explanation of the symmetry of the hydraulic-conductivity tensor and about the limited mention of previous studies of flow in anisotropic systems. The reviewers also commented on its present-day (1990's) contribution. A discussion on each of these concerns follows.

A recent reviewer of the primer, Paul Hsieh of the U.S. Geological Survey (written commun., May 22, 1990, and March 24, 1992), raises a question about the statement after equation C 2 in the primer concerning the symmetry of the hydraulic-conductivity tensor. Hsieh (written commun., March 24, 1992) indicated that

> * * *the conductivity coefficients in reference to the *x-y-z* coordinate axes are symmetric because the hydraulic-conductivity tensor is assumed to be symmetric. The symmetry is a direct result of Theis' assumption that there exist three mutually perpendicular directions in which the specific discharge is parallel to that of the gradient of head. In other words, the mathematical development from equations B 2 to B 9 already assumes that the hydraulic-conductivity tensor is symmetric. Thus, the finding that "the two subscripts can be transposed" is not an explanation of symmetry but a consequence of the original assumption.

It is doubtful that Theis was familiar with all the relevant literature and, given his inclination to derive the mathematics he needed to solve a particular problem, or to seek expert help with a particular solution, he may have considered it unnecessary to conduct a thorough search for prior contributions. Theis' reference to the book by Bear, Zaslavsky, and Irmay (1968) was a good choice because, besides giving a thorough analysis of flow in anisotropic media, the authors cite many of the original contributions to the development of this subject. For the interested reader, a review article by Maasland (1957) gives a thorough technical presentation of the theory of flow in anisotropic media and an excellent review of its historical development. Some of the earliest contributions to the theory of flow in anisotropic media date back to the 1930's, such as Vreedenburgh (1936). Furthermore, Maasland (1957, p. 218) credited Versluys (1915) for an important theoretical result concerning the existence of three unique, mutually perpendicular directions of anisotropy for a porous medium that can be represented by " * * *any combination of arbitrarily directed sets of parallel, non-intersecting, capillaries."

Recent reviewers of the primer expressed differing opinions as to its present-day (1990's) utility. Some reviewers argued that publication of Theis' primer is justified today mainly because of its historical interest; they contend that the effort needed to work through Theis' mathematical development is comparable to that needed to learn some tensor mathematics,which has the potential for broader applications than those addressed by Theis. They maintain that the typical hydrogeologist of the 1990's has a much better understanding of mathematics than did his counterpart of the mid-1970's; therefore, using the most elementary mathematics to introduce anisotropy is no longer necessary and efficient. Other reviewers argue that the level of presentation of the mathematical development in the primer would be appropriate for many hydrogeologists even in the 1990's and that some of the results, particularly concerning flow across dipping beds, may be useful to readers who may not even be able to follow Theis' elementary mathematical approach. The consensus of the reviewers past and present is that serious students can gain something from Theis' "A Primer on Anisotropy."

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Aquifers, Ground-Water Bodies, and Hydrophers

***By* C.V. Theis**

INTRODUCTION

Of all the terms that the U.S. Geological Survey, Water Resources Division ad hoc Committee on Redefinition of Ground-Water Terms considered, that of "aquifer" caused the most dissention within it. Even after publication of the committee's report, with a definition that was essentially that of Meinzer (Lohman and others, 1972, p. 2), the argument among ground-water hydrologists continued. Each side of the argument could find something in Meinzer's papers to justify their preferred usage.

The difficulty arises with respect to aquifers in which a water table exists. One group of hydrologists insists that the aquifer is coextensive with the formation; thus, the Ogallala aquifer is the Ogallala Formation. The other group insists that aquifer refers to only the basal, saturated part of the formation or other geologic unit; thus, the Ogallala aquifer is only the saturated part of the Ogallala Formation.

Inasmuch as intelligent students are on both sides of the argument, it is evident that some fundamental misunderstanding exists. The present author believes that we have made the word "aquifer" serve too many purposes, that it is time to examine the hydrodynamic ground-water system and consider carefully the elements of that system. There are three elements: (1) the water-bearing formation, (2) the water body, and (3) the porous medium affecting the flow in the water body. A scientific term should express one definite concept, and no other. These are three concepts, and if we want to deal with them scientifically, we should have one word or expression by which to refer to each concept, and this word should not refer to any of the others.[1]

THE AQUIFER

Confusion about the word aquifer began with its first use in English, and it seems to have had a rather obscure birth. According to Meinzer (1923b, p. 6) "The term aquifer was introduced from the French by Norton" (Norton, 1897, p. 130). This statement is inexact or perhaps untrue.

Figure 1 is a reproduction of Norton, p. 130. Norton explains his use of the term as follows: "The sand represents the permeable water-bearing layer, the *aquifer*, to revive a term of Arago's, and its outcrop between the basin rims the area of supply." Norton does not reference the origin of the word any more closely than this, but a paper by Arago in 1835 is cited on both pages 122 and 133 in other contexts. Arago was a French astronomer and physicist who died in 1853, three years before the publication of Darcy's "law."

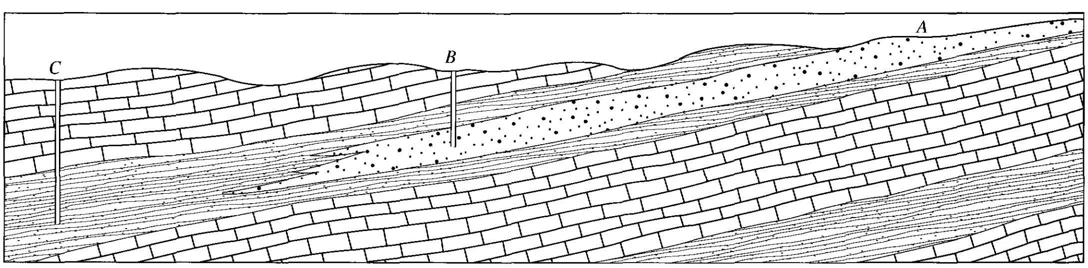

Figure 1. Progressive change in texture of aquifer *A*, from an open water-bearing sandstone at outcrop and at *B*, a successful artesian well, to a dry sandy shale at *C*, an unsuccessful boring. After Norton, 1897, fig. 31, p. 130.

[1]**Editor's note:** Whether consciously or not, Theis expresses in the preceding sentence thoughts identical to those of Meinzer (1923b, p. 1) in his introduction to Water Supply Paper 494, where the term "aquifer" was first formally defined.

The title of Norton's figure 31, which is a section along the dip of the beds, should be noted: "Progressive change in texture of aquifer *A*, from an open water-bearing sandstone at outcrop and at *B*, a successful artesian well, to a dry sandy shale at *C*, an unsuccessful boring." This somewhat peculiar statement is more or less explained by the concluding statement on p. 129, which refers to figure 30: "Terminal escape beyond the location of the wells is precluded when the water-bearing stratum runs out, is flexed upward, or becomes impervious from change of texture." Apparently, Norton believed that an aquifer needed a plug to keep the water from running out of it.

On page 131 of Norton's paper there is further description of how to keep water in an aquifer: "A useful variation of the illustration just described is obtained by using, instead of a bent tube as apparatus, a straight tube closed at one end and filled with water. If this tube is tilted at an angle and a hole is bored near the lower end, the water will jet to a height depending upon the difference in height of the jet as the water sinks in the tube, or as the tube is tilted at different angles. By filling the tube with sand and repeating the experiment, the diminished height of the jet shows the effect of the increased friction. Another hole bored beyond and below the first draws down the original jet and illustrates the effect of terminal escape."

At any rate, Norton had no idea of doing any quantitative work regarding an "aquifer," and his source, Arago, 20 years before Darcy had no such idea. Meinzer also had no idea of quantitative work at the time he quoted Norton's "aquifer." It means that the word "aquifer" never had a quantitative use.

Returning now to Meinzer's statement that Norton got the word aquifer "from the French," this implies that it might be a somewhat common French term. This is not the case; French writers on ground water do not use the term, at least in this spelling, either today or in the late 19th century. Although apparently Arago used this word in his 1835 paper, there appears to have been no such word in the French language in Norton's time nor at present. The French word is "aquifère," commonly used as an adjective, but sometimes as a noun, as is practiced in all languages--"The good die young." "None but the brave deserve the fair." The word "aquifère" is so common that there is no possibility that Norton could have considered that he was "reviving" it. That would be equivalent to Meinzer saying that he was reviving the word "water-bearing." The modern usage of "aquifère" as both adjective and noun is shown in Schoeller's definitions (1962, p. 155).

In the following quotation, the French words (and the French idiom where the meaning is clear) are used: "The formation (terrain) in which the water moves is called the water-bearing formation (terrain aquifère) or simply the aquifère. The *imperméable* is a formation less permeable than the *aquifère** * *. An *imperméable* floor is under [the aquifer], the *nappe imperméable* roof, above. *Imperméable* may be formed by an aquiclude* * *." We shall return to Meinzer's usage later.

In Norton's time, the best French information on ground water was probably in a text, "Les Eaux Souterraines" by Gabriel Auguste Daubree, published in 1887, 10 years before Norton's paper on artesian wells. However, Norton must have been unaware of Daubree's book; if he had known about Daubree, he would not have quoted Arago. Daubree was a pioneer geophysicist who mentioned the work of Darcy and Dupuit in "Les Eaux Souterraines" as well as the work done on the theory of ground water in Holland on the flow into the polders from the dunes to the sea behind the dikes. He discusses the assumptions necessary in applying the work of Dupuit, ascribes to him the conditions of flow in the "permanent regime," and says on his own authority that the same principles apply to the "non-permanent regime." He also describes some of his own experiments with a set of cells with partitions of chalk, and shows that after filling the end cell with water, after some months, the water had in part descended to the other cells so that the water level in all the cells showed a continuous slope from the first to the last. Daubree also discussed the effect of bank storage on the flow of streams, the ground water in the gravelly banks being added to in times of flood and feeding the stream in times of drought. He also noted that some hydrologists had tried to compute from field data the permeability of a formation, but had gotten very discrepant results, "no doubt due" to the difficulty of reproducing the nature of the actual aquifer. Daubree (1887, p. 53) knew that "* * *however permeable might be the rock, because of a resistance with which it opposes the flow of water, the upper surface of the saturated bed or nappe d'eau forms a curve inclined toward the discharge." He also knew that movement of the water filtering through the soil along an irregular channel that forms the interstices between grains of sand composing a permeable formation is very slow.

Daubree used "aquifère" almost entirely as an adjective: "sable aquifère, niveau aquifère, couches aquifère" (water-bearing sand, water levels, water-bearing beds).

Meinzer, in a single paragraph in Water Supply Paper 494 (1923b), first defined "rock formation" in a geologic sense, then "water-bearing formation," and finally an aquifer: "An aquifer is a formation, group of formations, or part of a formation that is water-bearing. The term ground-water reservoir is used as a synonym of aquifer." The emphasis is on the geologic formation, or group of formations, or member[2] of a formation. Equally consistent are Meinzer's other explicit definition (1923a, p. 52) and definition by inference (p. 312, par. K) "Great Plains Pliocene-Cretaceous province. The principal aquifers of this province are the late Tertiary sands and gravels (Ogallala formation and related deposits) and the Dakota sandstone." There can be no doubt that Meinzer, who gave wide currency to the word, considered the aquifer to be a geological formation both above and below the water table, or rather, without reference to the water table.

The chief alternative definition of aquifer, that it is the part of a formation below the water table, leads to some inconsistencies in its common use. You cannot recharge such an aquifer; it is already full. Similarly you cannot deplete an aquifer; no matter how much water is taken out, the aquifer is still full, at least up to the last drop, at which time the aquifer disappears. All that can be done is to thicken and thin the aquifer, which is hard to do with a solid even if it is porous.

There is even another kind of aquifer. This occurs when a widely extended water body stretches over more than one formation; thus we have the Floridan principal aquifer. Still another definition of aquifer would apply to each porous zone in a formation; for example Nye (Fiedler and Nye, 1933) called each porous zone in the "Picacho" limestone an aquifer.

Finally, "aquifer" forms a pitfall into which even the best writers are apt to fall. Thus, McGuinness (1963, p. 23) wrote, "The term 'aquifer' describes a body of rock * * *that is filled with water* * *." However, on page 30: "To the extent of their capacity to store and transmit water, the aquifers of this region function like aquifers anywhere else in providing storage space for water* * *." And on pages 39 and 40, the Ogallala Formation and the sand of the Nebraska sand hills are both aquifers. On the whole, McGuinness wrote of "aquifers" that were certainly *not* "filled" with water.

Perhaps it is of interest that the present writer has also been accused of using "aquifer" in both major senses.

Thus, "aquifer" has been used in so many different senses by so many people to express their own particular ideas that it has become an Alice-in-Wonderland word that means just what the author says it means. Worst of all, the author practically never tells us what he means. It has been used in so many different ways that it must be abandoned entirely as a scientific word or alternately to express *only* the original usage of it without any relation to the water table and only as a water-bearing formation or other water-bearing geological entity. The present writer prefers the latter course and will try to use that meaning entirely in the rest of this paper.

THE GROUND-WATER BODY

The ground water present in a formation or other geologic entity forms the ground-water body. It is the active part of the ground-water hydraulic system. The ground-water body is recharged, and the water in the water body discharges under natural conditions. The ground water occupies the whole aquifer if the system is confined and, in general, only the basal part of the aquifer in nonartesian systems.

The ground-water body is to the French the "nappe d'eau" or "sheet of water." The French phrase has much to commend it. It is shorter than ground-water body, especially orally. It is a concept clearly expressed in the French ground-water literature and very commonly used. It is much more common than "aquifère" as a noun.

Under water-table conditions, the recharge to the water body is episodic, and the natural discharge is more or less constant. Thus, in general, the water table fluctuates, and the ground-water body thickens in times of recharge, particularly in response to heavy precipitation, and thins in times of drought.

A cone of depression forms in the ground-water body in response to pumping. In confined water bodies, the cone of depression is superimposed on the normal potentiometric surface of the water body. The water moves, in general, in accord with the hydraulic gradients of the combined system, as was recognized by Slichter (1899, p. 368). Almost the same phenomena occur in a nonartesian water body. However the cone, in general, is distorted by the general movement of the water. This movement is, in general, so slow that it is important only when the time being considered is very long.

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[2]**Editor's Note:** Use of the word "member" is Theis' interpretation of Meinzer's intent. Meinzer's use of "part" may indeed have meant a further stratigraphic subdivision; but the more general expression may well have led to ambiguity and differing opinions among American hydrogeologists over what constitutes an "aquifer."

In general, as remarked above, the water moves along the hydraulic gradient, and more or less along the slope of the water table, in unconfined systems. However, in detail, it may diverge considerably from an inferred flow line, as will be discussed further when we consider the porous solid material that the water occupies.

Two properties of the water are very important. The first of these is its kinematic viscosity (dimensions L^2/T), which is its dynamic viscosity divided by its density. This represents the resistance of the water to its movement. The viscosity of water varies widely with temperature. The kinematic viscosity at 0 degrees C is six times that at 100 degrees C. In thermal areas, water may be in the form of vapor, and have even lower viscosity. And in permafrost areas, ground water may be in the form of ice, in which case the viscosity is essentially infinite.

The second important property of water is its compressibility, which represents the contribution of the water to the coefficient of storage of the system. Water is much more compressible than the most *permeable* parts of the ground-water system, for sandstones or even packed sand or limestone, have generally a compressibility of approximately one-tenth that of water.

It must be remembered that the water body or nappe d'eau is the primary part of the ground-water system, as the French recognize. American hydrologists must also realize that as a class they have become enamored of that trademark word "aquifer." For instance, we do not, in a strict sense, recharge or drain the aquifer. Inasmuch as the water body is contained in the aquifer, we sometimes use the elliptical expression of "depleting the aquifer," just as we often "drain the bathtub" after use, whereas we actually drain the water from the bathtub. Similarly, the Floridan aquifer and the Roswell artesian aquifer are misnomers. What is continuous in these concepts is the water body, which may cut across formation boundaries. If we recognize this, we would more properly write "the Floridan water body" and the "Roswell artesian water body." Or perhaps we could write the Floridan nappe d'eau and the Roswell artesian nappe d'eau.

THE HYDROPHER

The porous medium that the ground water saturates and that affects the movement of the ground water is the third element of the ground-water system. As stated above, one group of hydrologists wants to call this element the aquifer and as also stated above, "aquifer" means the complete formation or else it has no scientific validity.

I propose to call this porous medium that the ground water fills the *hydropher*. This term has the Greek roots for "water bearer," whereas aquifer has the Latin roots for the same meaning.

Although both terms mean the same etymologically, they are very different concepts. The aquifer has an existence in its own right; it is a geological entity, generally a formation composed in large part of permeable beds. The hydropher has no existence apart from the water body; if the water body is pumped dry, or otherwise depleted, there is no water in the medium and hence no hydropher.

The aquifer may be thought of as setting a limit on the size of the water body and on the size of the hydropher. In a confined water body, the water occupies the whole aquifer and, therewith, the hydropher. In an unconfined water body in an alluvial aquifer, the water body at the time of deposition of the aquifer filled the entire aquifer and, therewith, the hydropher. Later, in general, the water table stands lower, and the water body and hydropher occupy only the lower part of the aquifer.

Overall, the hydropher is characterized by an intrinsic transmissivity at any given time, which together with the kinematic viscosity of the water, controls the movement of the water under a potential gradient. As the water table rises and falls, the transmissivity may change drastically or, alternately, very little, depending on the permeability of the beds through which the water table moves.

In detail, the movement of ground water departs greatly from the simple movement suggested by an inferred flow line. All suites of samples from the drilling of wells represent in each suite a wide range of intrinsic permeabilities. If these permeabilities are multiplied by the thickness of the bed represented by the sample and then arranged according to increasing permeability, the range is approximately exponential. Quite frequently, the permeabilities range through about one order of magnitude. If the beds were continuous and of this range of magnitude, half the water would move through about 30 percent of the most permeable beds and the other half through 70 percent of the less permeable beds.

However, no two wells in the same formation have identical logs. The beds must therefore be, in general, lenticular. The phenomena of dispersion in the field show a thorough mixing of tracer both in the direction of flow and also laterally, perpendicular to the general direction of flow.

The character of flow must therefore be very erratic, with flow lines being refracted at every boundary between lenses of different permeabilities, in the same general horizon or in different horizons. The movement of the water is therefore very erratic, both in the horizontal and the vertical sense. Consequently, the potential gradients and, therefore, heads are more or less erratically distributed.

Well-designed potentiometers should show different heads along any vertical line. Ordinary wells without casing or with casing perforated throughout the permeable section, used in general for drawing water-table maps, tend to average out the potentials along their individual depths. In general, water should be moving vertically in such wells even when they have been unpumped for some time. Such wells must disturb the flow field in the ground water.

Hydrophers [in sedimentary rocks] apparently nearly everywhere contain silty laminae or lenses. These are particularly important in confined water bodies, for, with the reduction of pressure within the water body and the consequent increased pressure on the hydropher itself, the fine beds are greatly compressed or compacted. Such irreversible compaction in fairly thick confined aquifers results in ground settlement, as in the case of the San Joaquin Valley, California, in Mexico City and many other known places, and probably in many places where the settlement has as yet not been recognized.

The results are most apparent in confined ground-water systems in which the effects of well discharge spread rapidly. However, the same results would come about by lowering the water table in an unconfined system. With an equal general drawdown and an equal thickness of silty beds, the effects would be the same as in a confined system. The ground settlement would be just as great. Of course the time taken to produce a given semi-permanent drawdown would be much greater in the unconfined water body.

When an unconfined water body is being depleted, successively fewer lenses must carry the water. There are fewer opportunities for the water to move vertically to find coarse, very permeable lenses. Thus, the average permeability of the thinning hydropher probably decreases considerably, and the decrease in transmissivity probably accelerates as the water table nears the base of the formation.

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Analysis and Critique of "Aquifers, Ground-Water Bodies, and Hydrophers" by C.V. Theis

By **Alfred Clebsch**

GENERAL REVIEW

"Aquifers, Ground-Water Bodies, and Hydrophers" was first written by C.V. Theis in 1983; it now includes editorial changes dictated by him a few weeks before his death in 1987. The paper is an outgrowth of committee deliberations that led to the publication of Water-Supply Paper 1988 (Lohman and others, 1972) and represents Theis' effort to resolve the semantic and conceptual confusion implicit in Meinzer's definition (1923) of the term *aquifer.*

The Committee on Redefinition of Ground-Water Terms of the Water Resources Division, U.S. Geological Survey, chaired first by Arthur M. Piper and later by Stanley W. Lohman, was assigned the task of redefining ground-water terms and concepts then in use within the USGS and establishing consistent units as the basis for the definitions adopted.

Even though the committee's readoption of Meinzer's definition of *aquifer*, essentially a stratigraphic or rock-type definition, emphasized Meinzer's intent that the term include the unsaturated part of the permeable material or rock unit, the committee did not incorporate this concept into its own definition. Several members of the committee and numerous ground-water hydrologists in the U.S. Geological Survey continued to think of the *aquifer* as only the saturated part of a permeable rock unit. Debate on the subject, both in correspondence among committee members and apparently in meetings of the committee, was intense. For years afterward, Theis continued to feel that the committee's efforts had fallen short of its objectives. The omission of *water body* from the list of defined terms and failure to provide a definition of the saturated part of the aquifer, significant only in the water-table case, with sufficient completeness to eliminate the controversy, led Theis to write this paper.

Although Theis apparently considered the paper sufficiently complete in 1983 to submit it to several reviewers for comment, he also dictated an addendum to it just a few weeks before his death. The addendum has not been incorporated into this version; it is less articulate than the text presented here, in part because it contains references to illustrations that had not yet been drafted or to previously published ones about which there is considerable uncertainty, and the ideas being developed were not completed. The several pages of additions deal with the statistical distribution of porosity and permeability in sedimentary rocks, a subject on which Theis had published earlier (1962a).

The text presented is virtually as Theis wrote it, except for minor changes that had been suggested by the reviewers who read the paper in 1983 but had not been implemented by Theis. The changes related primarily to the work of the Committee on Redefinition of Ground-Water Terms. Those changes and additional editorial changes made by Theis on photocopies of the text but not transferred to the main working copy have been incorporated. In several instances, Theis wrote different sets of notes to be added to or incorporated into the manuscript, some with only slight differences in wording from others. The notes whose wording seemed most appropriate to this writer were included. A few such notes, which appeared to be digressions or to conflict with other parts of the paper, were not used.

The paper should be considered incomplete, primarily because of the omitted additions. Nevertheless, it contains important lessons in semantics; the juxtaposition of French terminology with American usage provides an interesting contrast. Theis' logic argues not so much in favor of the term aquifer as *formation* as against the term aquifer as the *saturated part* of the formation; however, any emphasis on the stratigraphic terminology probably stems from his strong belief in the necessity of understanding the "plumbing system" through a knowledge of the geology, plus his tendency to be an etymological purist. He also states the case, but does not develop the arguments to support it, that the term *aquifer* should be used only in a nonquantitative sense, and one might speculate that his emphasis on *water body* and *hydropher* might have led to proposing that those terms form the basis for quantitative analyses and discussions.

An example of the Committee's debate and of Theis' contribution to it is contained in a memorandum he wrote to committee members on August 13, 1969:

<u>On aquifer</u>

The controversy over *aquifer* has generated a little thought on my part or perhaps brought to the surface something that has been in my mind for some time.

But first to the late correspondence.

[There follows a rebuttal of points made in correspondence from other members of the committee and the results of informal polls on the use of *aquifer*. Then,]

Now to the result of my thinking. As Stan [Stanley W. Lohman] shows, I have been very sloppy in my writing--and Meinzer let me get away with it at the time he was reading all reports. It *is* convenient to write "aquifer thickness times hydraulic conductivity;" it saves thinking. But to consciously do so by redefining "aquifer" makes us define a porous solid that at one time thickens and another thins, that now contracts and then expands laterally, that can entirely disappear and later be recreated, apparently for the sole purpose of being able to write this phrase.

Which leads us to the question of what good is the word anyway? I believe with careful consideration of our problems it will soon become obsolescent. We deal with water bodies; they are the dynamic things that furnish our water, that are contaminated by our wastes, that are depleted by our use. The heads in them are lowered by our pumping. The matrix is static.

This criticism of the word applies to both geologic and quantitative aspects of ground water. The French apparently have no use for the word. Daubree in the first volume of Les Eaux Souterraines (1887) has 446 pages of text, describing geologically the occurrence of ground water in many formations all over the world. I believe he never uses the word aquifer; he deals with "nappes d'eau." Schoeller in his "Les Eaux Souterraines" (1962) has 579 pages of text dealing with all the theory of ground water including the quantitative. He defines aquifère--"le terrain dans lequel l'eau circule"--and apparently never uses the word again. When he quotes Americans he is compelled to use "la formation-aquifère." Otherwise he uses "nappes d'eau."

In order to describe the piping system in nature and where the ground water occurs, it is generally necessary and always advisable to define the water body stratigraphically. However, many of our ground-water bodies extend laterally through more than one stratigraphic formation, particularly in limestone formations. Instead of inventing a mythical aquifer (for example., the Floridan aquifer), recognized because it contains a continuous water body, it would be more specific and cogent to describe a water body continuous through such and such formations. Even in the geologic sense, "aquifer" has outlived its usefulness, and is unnecessary, as Daubree demonstrated.

In quantitative studies, we study the natural flow of ground water, or we withdraw from the water body and measure the lowering of the water table or other potentiometric surface. We recognize the pertinent characteristic of the containing medium only by the rate water (or some other fluid in the laboratory) flows through it, and in the field only by the way the water body changes its dimensions when it is tapped by an operating well. That the focus can be put on the water body instead of the containing medium is shown by Schoeller.

In only one group of phenomena is the medium dynamic. This is that associated with the "compressible artesian aquifer." Of course, a large fraction of the coefficient of storage is inherent in the water body and is not properly ascribed to the "aquifer," being associated only with the porosity of the medium, and that part due to the deformation of the medium, where significant, is almost certainly associated with poorly permeable lenses that in themselves would probably not yield water to wells in economic quantities. "Aquifer" would find its greatest justification here, but "matrix" or "containing medium" even here would serve the purpose.

To sum up, we should define "aquifer" because we are at least temporarily stuck with the word, but in our own writings and in our suggestions to younger writers, we should be careful to distinguish between characteristics of a water body and those of the containing medium. If we do we will be less sloppy in the use of the word "aquifer" and not use it [in] as many senses as is convenient at the moment.

In conclusion, I will make a stab at defining *water body*, not for inclusion in the report, because it is likely to be controversial just now, but to see what objections there are to the concept. Some ideas are taken from Schoeller's definition of a "nappe."

A ground-water body is a complete assemblage of water at some place within the zone of saturation that is continuous through interstices between sand grains or fissures or channels and may be, or in general must be, considered a unit in its major hydrodynamic properties. The water in it moves predominantly laterally, and the total flux through it is a substantial or important part of the regional ground-water flow. Most water bodies have physical limits, but if properly defined by the writer, water bodies may be considered to be such continuous bodies between other types of hydrologic boundaries.

"C.V."

In retrospect, it seems unfortunate that the work of the committee was not prolonged, at least to the extent of incorporating Theis' definition, or a consensus version thereof, of *water body* into its report. The committee used the term in several definitions, but did not define it explicitly. If *water body* had been defined in Lohman and others (1972), the ambiguity between *aquifer* in Meinzer's original meaning and *water body* in those permeable zones that cut across stratigraphic boundaries might have been reduced.

The excerpt from Theis' correspondence predicts the death of *aquifer*, but in this paper, written more than a decade later, he argued in favor of the Meinzer definition. Furthermore, the interest in the late 1980's in naming aquifers and in prescribing rules for *hydrostratigraphic* nomenclature (Seaber, 1988) demonstrate the inaccuracy of his prediction.

The classical Meinzer definition of *aquifer* was sharpened by the Committee on Redefinition of Ground-Water Terms by its reference to Meinzer's intent that the term incorporate the "unsaturated part of the permeable unit," even though the committee report left the matter hanging by failing to redefine *aquifer* to include it. This definition, however, neglected those "aquifers" for which there is no correlation between hydraulic conductivity and stratigraphic boundaries. Certainly, stratigraphic correlation provides the most convenient means of extending subsurface knowledge of aquifer distribution, especially where the permeability trend of a given stratigraphic unit is consistent. Indeed, utilization of all the geologic information available is essential, although in some instances it is still insufficient for a thorough understanding of aquifer distribution and properties. But the criteria for defining "formations," a term that was much less formal in Meinzer's day than now, do not include characteristics that influence ground-water flow, except incidentally or indirectly.

Part of the difficulty with *aquifer* comes from the fact that the field of stratigraphy has formalized, and to a degree preempted, *formation* by imposing highly detailed and explicit rules governing the use of the term; hence, the use of such expressions as "body of rock" in one of the more widely distributed definitions of "aquifer" (Bates and Jackson, 1987, p. 33). This definition has both disadvantages and advantages.

Although it lacks the connotation of tabular geometry conveyed, at least to this writer, by "formation," it embraces aquifers that consist of fracture zones in metamorphic and plutonic igneous rocks, basalt flows, interflow zones, and other permeable rock masses that do not meet the accepted criteria for "formation" most commonly applied to sedimentary rocks. The argument can be made that the definition should *not* imply a particular geometry, but this tends to ignore the fact that most aquifers *are* tabular, or roughly so, in response to depositional, volcanogenetic, or tectonic environments, or a combination thereof.

The concept of mappability is essential to the delineation and depiction of geologic units and aquifers as well. Indeed, the concept of mappability may have provided the rationale for Meinzer's use of *formation* in the definition of aquifer in the first place, and any revision of *aquifer* should embody mappability.

As hydrogeology continues to evolve as a more sophisticated branch of the earth sciences, it becomes increasingly dependent on the science of stratigraphy and the methodologies of subsurface geology. That dependency is critical to an appropriate understanding of the flow paths of ground water, which respond to a usually complex permeability distribution. Such an understanding must come from definition of the spatial distribution of mappable rock properties, correlation of those properties with porosity and permeability, and relating them to established rock-stratigraphic units.

The science of stratigraphy has advanced, with an increased emphasis on depositional environments and other purely geologic, geophysical, or paleontologic criteria, but its linkage with ground-water hydraulics has weakened. Ground-water hydrology has been so preoccupied with improved analysis of flow systems that little attention has been paid to advances in knowledge of permeability trends in relation to depositional environments and processes. Concurrently and somewhat paradoxically, the increased importance of ground-water geochemistry, and especially the chemistry of interactions between the aquifer matrix and constituents of wastes entrained in the water body, have demanded a more thorough knowledge of mineralogical composition and geochemical characteristics—properties that can be deduced only from an improved understanding of rock chemistry and mineralogy as well as depositional and diagenetic environments and processes.

Heightened interest in fracture permeability and solutionally altered permeability has in recent years further weakened the concept of aquifer-as-formation as defined by Meinzer and successors, and has led to the definition of "aquifers" that cut across geologic units, thus increasing the difficulty of subsurface correlation by orders of magnitude.

HYDROPHER

It appears that in proposing the term *hydropher*, Theis was attempting to supply an alternative term to those ground-water hydrologists who think of the saturated part of a permeable body of rock as the *aquifer*. In devising a term for that part of the containing medium that is coextensive with the water body, he provided a logical basis for the expression "transmissivity equals hydraulic conductivity times *hydropher* thickness." Conceptually, this conveys the potential variability of transmissivity under water-table conditions.

Hydropher would have little application in situations where aquifers are predominantly artesian with little or no chance of total or partial dewatering (unless it catches on as a "quantitative" alternative for *aquifer*). However, in large parts of the Western United States, for example, it could have wide application where ground water occurs in deep alluvial basins, many of which are only partially filled and many of which have experienced large declines of the water table. Furthermore, whether widely applied or not, its primary significance seems to be in its clarification of *aquifer* as the total thickness of permeable material.

AQUIFER—FROM THE FRENCH?

As is apparent from Theis' discussion in this paper, the French usage of ground-water terms was of considerable interest to him. It seems likely that his interest in Daubree, Darcy, Dupuit, and other French writers on ground water fostered the curiosity that led to his careful reading, and translation into English, of Schoeller's (1962) text.

Theis questioned Norton's (1897) attribution of *aquifer* to Arago. He obviously knew something about Arago's prolific output of scientific writings on numerous subjects, but evidently he did not read the 1835 Arago paper cited by Norton (1897, p. 124) in connection with flowing wells. He also called attention to the fact that Norton did not provide a detailed citation for "reviving the term of Arago." Theis, as well as Meinzer before him, seems to have assumed that Norton's attribution was accurate. Although the nature of Norton's reference is such that the term could have been used in another of Arago's papers, not cited by Norton, this seems unlikely. The Catalog of Scientific Papers (1800-1863) published by the Royal Society of London (1867) includes 116 titles by Arago in addition to 7 coauthored papers on a wide variety of subjects, including comets, glaciers, climate change, volcanoes, solar eclipses, and sunspots, but only one dealing with underground water.

The cited paper was published in French (Arago, 1835a) and in English the same year (Arago, 1835b). Neither contains the word *aquifer*. Presumably, the English version was written by Arago, as it contains no acknowledgment of a translator.

In the French version, Arago used *nappes d'eau souterraines* several times, and the following terms once each: *nappe liquide*, *couche d'eau*, *nappe souterraine*, *nappes aqueuses*, *couches aquifères*, and *nappes aquifères*. He translated *couches aquifères* as *water carrying beds* and *nappe aquifère* as *water*; he also used *water* in the English version for *nappe* in the French, apparently departing from the literal where context permitted.

It appears then, that Norton either took the liberty of anglicizing *aquifère* to *aquifer*, was careless in copying from the French, or made a poor choice of words when he claimed to "revive" *aquifer*. If, instead of "to revive* * *," Norton had said that he was "adapting" *aquifère* to the noun, *aquifer*, or that his term, *aquifer*, was derived from *aquifère*, he might not have incurred Theis' criticism.

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C.V. Theis, The Man and His Contributions to Hydrogeology

By Robert R. White and Alfred Clebsch

INTRODUCTORY NOTE

In the early 1980's, the senior author of this chapter worked in an office at the U.S. Geological Survey (USGS) Water Resources Division District Office in Albuquerque, N. Mex., a few doors from C.V. Theis' office. At White's suggestion, Theis began writing an autobiography, and worked on it periodically for the rest of his life. The autobiography, which did not go past the mid-1940's, is the source of most of what we know about the early part of Theis's life. Other writings by Theis describe other parts of his career. The draft of a presentation entitled "Theis's Crisis," which he gave at several USGS short courses on ground water, first in 1967, tells much about his work on the non-equilibrium equation. His correspondence with C.I. Lubin is also very informative on this subject. In later years, he wrote an "Addendum to Theis's Crisis" (May 1980) and "Theis's Crisis--Addendum #2" (July 1981). The two addenda add little of substance to the "Crisis" story, but by implication indicate the complexity and controversial nature of Theis' relationship with some of his Washington colleagues, notably O.E. Meinzer. Theis also wrote short autobiographical notes for the USGS for administrative purposes. All these documents were consulted during the preparation of this biography. This biography is, then, to a considerable degree an edited compilation of C.V. Theis's own writings about his life and career. (Where possible, Theis's autobiography was checked with other sources).

From the 1940's on, however, information on Theis's career had to be pieced together from records in his files, including correspondence related to his work, personal journals that he kept during the 1940's and 1950's, and his files relating to the projects that he worked on in the 1950's and 1960's. In the introductory comments in some of his published reports, Theis provided information about his work schedule on that particular project; these comments often give information about his work that would not otherwise be available. An interesting view of Theis, from an oral-history perspective, is presented in a videotaped interview conducted in December 1985 by John D. Bredehoeft. In a condensed version that has been widely exhibited, Theis gives a highly personalized commentary on various developments in ground-water hydrology, ranging from his own contributions to transient hydraulics to his ideas on solute transport, including theoretical and experimental contributions of others. All these documents, as well as many others, are included in the C.V. Theis Collection at the Center for Southwest Research, General Library, University of New Mexico, Albuquerque, New Mexico 87131. In addition to information from these sources, coverage of the period between about 1957 and 1980 is based in part on material from Theis' files and on personal recollections of the junior author.

The account of the latter part of Theis' life has, of necessity, been presented differently than the part based on Theis' autobiography; whereas his account was strictly chronological, the latter part is organized around activities that may have overlapped in time.

Critical reviews of the manuscript by Roy Cruz, John Flager, Bobbie Cloud, and William E. Hale are gratefully acknowledged.

CHARLES VERNON THEIS

Charles Vernon Theis was born in Newport, Ky., on March 27, 1900, the second son of Edwin David and Ida Holbrook Theis. His older brother, Raymond, was born in 1896. When Theis was christened at the age of four, he was allowed to choose his own middle name. He was at the time interested in the story of George Washington and his home, Mount Vernon, so Theis chose Vernon as his middle name, though he later grew to dislike it. In later years he was known by almost everyone as C.V. Why was he C.V.? Why wasn't he Charlie? We do not know. His demeanor elicited respect. The formal caption on the frontispiece is out of respect; elsewhere we refer to C.V. His peers and friends called him C.V.; Gladys, his wife, called him C.V.; he referred to himself as C.V. Subordinates and deferential coworkers referred to him as Dr. Theis. A very few close friends addressed him as Charles; he did not like Charlie and no one who really knew him called him that.

Both boys excelled in school. Before C.V. was old enough to attend school, he studied the books that Raymond brought home, so that by the time he entered the first grade, he could do all the mathematics problems through the section on short division in McGuffey's primer.

When Theis completed the fourth grade, his family moved to a farm in the Oklahoma Panhandle. The farming venture proved to be unsuccessful; by the beginning of the school year, the family had moved to Guthrie, Okla. In Guthrie, each school grade was divided into A and B sections. The principal wanted to put Theis back half a grade, but his mother insisted that he could do the work in the fifth grade, so this was where he was placed on a trial basis. After a month, however, he was advanced half a grade because of his mathematical skills. A few months later the family decided to move back to Newport, where there were no half grades, so Theis asked to be advanced another half grade, which was done.

After his family returned to Newport, it appeared that Theis was ahead of classmates in the corresponding Newport grade, and so he asked to be advanced another grade. The result of all these changes was that he left Newport after completing the fourth grade, spent a year in Guthrie, and returned to Newport to enter the eighth grade. He was, therefore, two years younger than his classmates for the remainder of his time in public school. He never had any trouble with the academic work, but he was later to write that this difference in age caused "a certain diffidence and lack of assertiveness and easy discouragement" on his part.

Theis graduated from Newport High School at the age of 16. Not having enough money to attend college, and not being certain about what he wanted to study, he spent a year working as office boy in several places, primarily at the Rotary Club in Cincinnati, Ohio (his maximum salary was $8 per week in this position).

Having saved some money from his office job, Theis entered the civil engineering program at the University of Cincinnati, in autumn 1917. The course of study involved co-op work (one of the first work-study programs of its kind in the country). The first two years included summer field work in engineering, and the last three years embraced a progressively greater amount of practical work experience. Theis worked for a construction company for several months during his first year, and during spring and summer 1918, he worked on a surveying crew with the Miami Conservancy District around Dayton, Ohio.

The United States entered World War I on April 6, 1917, while Theis was still working for the Rotary Club; he walked home that evening to the sound of bells ringing and whistles blowing to mark the event. He registered for the draft in early 1918 and was inducted into the Army on October 1, at which time he was assigned to the Student Army Training Corps at the University of Cincinnati. On his second day in the Army, Theis reported for sick call with influenza and was sent home across the Ohio River to Newport. He recovered within a week, but by this time the camp at the university was quarantined because of the flu epidemic, and he could not return. Theis and some others who were quarantined out of the training camp were assigned for a few weeks to canvass certain districts in Cincinnati for rooms for war workers who would be coming to the city.

Theis was allowed to return to the university campus on about November 1, having missed a month of classes and Army training. However, there had been too many students in the hospital with the flu and too much war excitement for much academic progress. The war ended on November 11, and the student soldiers were discharged before Christmas.

During summer 1919, Theis did his co-op work as a carpenter's helper at the Englewood Dam site, north of Cincinnati on the Miami River. The chief engineer on this project was a competent, self-taught man named Arthur Morgan, who took a special interest in the co-op students. This project may have been Theis' introduction to the field of hydrology.

Theis' last three years of co-op work were with the Bridge Section of the Kentucky Highway Department at Frankfort. He considered these to be his best years of co-op work. During this field work, the co-op students stayed at the Y.M.C.A. on the south bank of the Kentucky River. An advantage of staying at the Y.M.C.A., as Theis saw it, was that one of the older bachelors there had a set of "Dr. Eliot's 5-foot shelf of books," which consisted of classics of English and European literature. At times when Theis had no pressing social engagements, he read extensively from this set of books.

Theis was among the top ten students in his class every semester as an undergraduate; in his third year, he was elected to Tau Beta Pi, the honorary engineering society. The members of the society voted on the acceptance of new members, and it was because of this that Theis became aware of another student, Clarence Isador Lubin. Lubin was studying chemical engineering, but he had always been in a different group of co-op students, so Theis had never met him. When Lubin was nominated for Tau Beta Pi, Theis voted against him, based on what he had been told by some of the other members. At the next meeting, however, a member who was in the class ahead of Theis defended Lubin. During the discussion that followed, Theis quickly decided that the feeling against Lubin been told by some of the other members. At the next meeting, however, a member who was in the class ahead of Theis defended Lubin. During the discussion that followed, Theis quickly decided that the feeling against Lubin was part of an anti-Jewish bias on the part of some of the membership. Theis called for a new vote and supported him, but Lubin's nomination was again defeated. Theis later got to know Lubin and considered him an excellent student. More than a dozen years later, this friendship bore fruit when Theis sought Lubin's assistance on a critical mathematical problem. Several decades later, in recounting the story to his secretary, Theis said, "So you see, if you listen to the wrong voices, you are apt to make the wrong choices" (Bobbie Cloud, written commun., May 4, 1992).

Theis received his civil engineering degree in 1922. Soon after his graduation, he was offered an assistantship in the Geology Department at the University of Cincinnati. He thought that he would take this opportunity to learn enough geology to work with foundations or tunnels or some other aspect of engineering in which geology would be a help. His interest in geology, however, soon caused him to change the direction of his career.

Professor Otto Von Slichten, who taught engineering geology and mineralogy to the engineering students, was responsible for getting Theis a position in the department. Theis had an office across the hall from Von Slichten's office and worked closely with him. During his first year, Theis taught some laboratory sections of mineralogy and geology for engineers. In his second year, he was appointed a half-time instructor. He attended faculty meetings and was in the unusual position of being a doctoral candidate who was, to a great extent, a colleague of his professors.

Although Theis had a particular fondness for Von Slichten, he felt that Professor Nevin Fenneman had the greatest impact on his development as a geologist. He enrolled in Fenneman's course on the physiography of the United States and took to heart his professor's frequent admonition to "Get the physical conception of the process!" During an oral quiz from Fenneman one Saturday morning, Theis felt that he was not very sharp in answering the questions, so he confessed to Fenneman that he had been to a dance the night before and had talked to a girl until 3 o'clock in the morning. Instead of chastising him for a lack of dedication to his studies, Fenneman replied, "I think you have a better physical conception of these processes than most!" Years later, when it seemed that Theis' ideas on aquifer analysis were not being accepted, he remembered Fenneman's comment and took comfort in the thought that perhaps he did, after all, have a good physical conception of the process.

During his undergraduate co-op work in Frankfort, Theis had done some moonlighting with the Kentucky Geological Survey drafting maps and diagrams. In graduate school, he wanted some summer work relating to geology, so he again approached the Kentucky Geological Survey. As a result, he was hired for several summers to do reconnaissance structural mapping using the "Fireclay" coal as a marker bed and some of the other coals and one thin limestone as key horizons.

There were few roads in the Kentucky mountains in the mid-1920's, so almost all of his travel was done on foot. Late every afternoon, he would stop at a house and ask, "Can you put me up tonight?" In perhaps 200 nights spent in the mountains during several summers, he was turned away from houses only twice—once because of illness in the house and once where several men were drinking so they could better enjoy a religious revival meeting.

One important and lasting result of his summer work in Kentucky is best described in Theis' own words:

> In 1926 I worked in Henderson County, Kentucky, for the Kentucky Survey on a program which I intended to be also my thesis study. I stayed in the town of Henderson, where I became friendly with the County Agriculture Agent. At his request I went out one Thursday night to help him set up for a propaganda movie show to a group of farm women who were in an extension camp. The movie was very boring and as the projection was going smoothly I had time to observe a girl [whose name turned out to be Gladys Huling] lying on a cot and evidently bored also. I wandered out on the porch where there was a full moon. The girl came out also. We started up a conversation and finally went out on the porch steps where we would not disturb the people in the meeting. I found she was teaching basketry and other artistic endeavors to the farm women and had been in several counties at similar meetings before and had seen the same movie at all of them. Also, that she expected to attend art school in Cincinnati the next year and would go to Henderson the next day. So we made a date for the following night.
>
> Everything went well on the date and so she accepted my invitation to go with me on some work on Saturday and then we spent all Sunday together. After about a year in Cincinnati we got engaged and as soon as I returned from my summer in Utah we were married [on October 14, 1927]. This was 58 years ago and so it has been a fairly successful marriage.

This rather matter-of-fact account may belie the degree to which Theis was romantically smitten with Gladys Huling. The poet in him was inspired to write, in part:

I sent my heart upon the seas,
    It felt each wind that blows.
At times, becalmed, it aimless went
Till God in mercy breezes sent;
    But gale or calm, I raised one psalm:
"Oh, bring my heart to port."

I sent my heart upon the seas,
    And ne'er could find repose
Until one night, its course it strayed,
    A beacon saw, held by a maid;
    Abandoned chart, I knew my heart
Had come to port.

No more my heart goes on the seas,
    In flowered gardens now it goes;
    It breathes the fragrance of a rose,
    It basks in light a warm eye glows.
    Of joy the sum! My heart has come
To port.

In 1927, Theis received a government appointment as a Junior Geologist (the salary was listed at $2,000 per year, but he was initially scheduled just for summer work). He worked for a few weeks in June on his Henderson County project and on July 1 reported for duty with the U.S. Geological Survey in Moab, Utah. He worked with Arthur A. Baker mapping the geology along Indian Creek to its confluence with the Colorado River.

In June 1929, Theis received his Ph.D. in geology, the first doctorate in geology granted by the University of Cincinnati (fig. 1). This event was somewhat overshadowed by the death of his mother from cancer shortly thereafter. As soon as classes had ended in 1929, he began work with the U.S. Army Corps of Engineers in Cincinnati. He primarily worked on damsites around Cincinnati, but on weekends he worked on other problems that interested him, such as a correlation of monthly pan evaporation with monthly records of temperature, insolation, vapor-pressure deficit, and wind movement.

Theis's work with the Corps of Engineers was done under his Civil Service appointment as a Junior Geologist. During this time, he applied for advancement to the level of Assistant Geologist (at $2,600 per year), and eventually he was offered a position at that level with the Division of Ground Water (later Ground-Water Branch) of the U.S. Geological Survey. He entered on duty with the Survey on July 1, 1930, on a basis that he later described as "forever."

His first assignment was to do a ground-water study of 12 counties in south-central Tennessee. David G. Thompson, who at that time was the right-hand man of Oscar E. Meinzer, Geologist-in-Charge, Division of Ground Water, joined Theis in Tennessee for a week to get him started in the Survey way of doing things; they met on the train from Cincinnati to Nashville. Theis's wife, Gladys, went with him to Tennessee and often accompanied him during field work. When he collected water samples at wells, she would run the hardness test with a soap solution; interestingly, the results of the onsite hardness tests revealed flaws in the water-quality analyses being done for the project at a nearby university.

At the end of the 1930 field season, Theis went to Washington to work on his report (which was published in 1936 as USGS Water-Supply Paper 677). It was at this time that he first met Meinzer. Their relationship was to be a bit rocky at times, although they treated each other with respect and courtesy.

Figure 1. C.V. Theis on the occasion of receiving the degree of Doctor of Philosophy (Geology) from the University of Cincinnati, June 1929.

In the spring of 1931, Meinzer was chairman of a committee trying to organize a Section of Hydrology in the American Geophysical Union (AGU). Robert E. Horton was vice chairman of this committee. Meinzer asked several men in the Division of Ground Water to present papers at the AGU meeting that year. Theis recalled what happened at this 1931 meeting during his acceptance of the Robert E. Horton Medal in 1984:

> While I was working with the Corps of Engineers, I became interested in reservoir evaporation, among other things, and as a start, I tried to develop on my own time a relationship between monthly values of evaporation from a standard pan and monthly values of insolation, vapor pressure deficit, and wind movement.
>
> I got a fairly good correlation for the places and years for which data were available. So when Meinzer asked me to give a review paper on evaporation, I included my own work. Meinzer did not like this. However, the meetings were imminent, and so my own work remained in the paper. At the end of the meeting, Horton came forward and said to me, "You might have been in my office! I used about the same data as you did, but you got a lot closer correlation than I did." This was in Meinzer's hearing. The next week, he came into my office and said, "It seems that I misjudged your work."

Because of financial difficulties associated with the Great Depression, Theis' project in Tennessee was not funded for 1931, so he was sent to eastern New Mexico to do a ground-water study in Roosevelt and Curry Counties, with emphasis on the Portales area. He began work on July 15, 1931, and soon found that he very much liked working in New Mexico; in particular, he liked the dry climate. Theis did a geologic reconnaissance, and during

August he obtained depth-to-water data on about 200 wells. On November 17, after irrigation withdrawals had ceased in the area, he conducted a 7-hour aquifer test and then calculated permeability using the Thiem equilibrium method. He was not pleased with the results. He concluded that the test (based on a 650 gallon-per-minute pumping well and four observation wells) gave results so divergent that they could not be used to establish the permeability of the aquifer in the area. (Reports based on this study and others are listed in the "Bibliography of C.V. Theis" in this volume.)

Theis left Portales on November 28, 1931, to return to Washington, but he was back in New Mexico in August 1932. This time, however, he spent most of his time in Lea County. S.S. Nye had worked in Lea County in 1929 and 1930, but the project was unfinished when he retired. Nye had already inventoried the irrigation wells, so Theis devoted much of his attention to determining permeabilities along the western escarpment of the plains. Samples of the water-bearing material were taken with as little disturbance as possible and were sent to the USGS hydrologic laboratory for a determination of permeability. For his hand-coring apparatus, Theis used a 3-1/2-inch-diameter cylinder with a hacksaw blade bent around it for a cutting edge. He found that obtaining a core without considerable disturbance of the material was difficult.

Theis went back to Portales in December 1932 to do some additional work on his Roosevelt County study and then returned to Washington. He was back in New Mexico during the field seasons of 1933 and 1934. Soon after the inauguration of President Franklin D. Roosevelt in March 1933, money from the Public Works Administration became available for government agencies. Two other USGS employees, Harry P. Burleigh and Herbert A. Waite, soon joined Theis in Portales. After a short time in Portales, Burleigh and Waite went to Amarillo, Tex., to set up an office. Theis followed them to Amarillo after about a month, and he thus had an opportunity to get a better picture of the High Plains water body because he was able to work in a different area.

It is not known exactly when Theis began thinking about the need for a non-equilibrium equation to be used to analyze aquifer characteristics, but the need became apparent to him as he tried to understand ground-water conditions on the High Plains. The methods that were then available were clearly not satisfactory.

At that time, it was commonly thought that there was a "safe" yield to every ground-water basin which, if not exceeded, could be withdrawn indefinitely. At Portales, the water-level records showed that the water table was slowly declining; however, the High Plains aquifer extended more than 100 miles to the east, north, and south. The water-level data indicated that the ground-water system was in a transient state, but the existing theory held only for an equilibrium state.

Many years later, Theis presented "Theis's Crisis,"[1] in which he described his thought processes while considering this problem:

> My first attempt to get at the transient problem was to take Thiem's equation for confined conditions, apply it to the ground-water body with a free surface, and imagine that the water withdrawn from storage was miraculously conveyed to the outer rim of the Thiem's cone and percolated from there to the well. I could then compute the volume of this Thiem's cone, multiply it by the specific yield as I then called it, equate this to the rate of pumpage times the time and, of course, get an equation for the external radius of the Thiem's cone in terms of time. This can be then substituted for the value of the external radius in Thiem's equation. What you get is a transient equation which is the same as the present non-equilibrium equation, excepting that the well function of *u* contained only the log term. The constant and the long power series were missing. As a matter of fact, this would have given me a handle with which to think about pumping projects in the High Plains if I could have trusted it, for it indicated it would take hundreds of years for this cone to reach the edge of the water body. But it was profoundly unsatisfactory theoretically. I saw no way of assessing the error in the equation that would arise from my assumption of miraculous translation of the water withdrawn from storage to the rim of the cone. Moreover, Thiem's equation requires a discontinuity where the cone of depression meets the water table, that is, it requires an edge in the water body, and that is manifestly impossible. There was apparently no hope of testing it out against the data from a pumping test. And so the matter remained in abeyance for some time.

In March 1934, Theis, Burleigh, and Waite went to Dallas for the annual meeting of the American Association of Petroleum Geologists (AAPG). There they met with Oscar Meinzer and discussed the High Plains project. Half jokingly, Theis told Meinzer that they needed a Jewish mathematician on the staff to solve their ground-water

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[1]**Editor's note:** The title, "Theis's Crisis," was not Theis' idea; it was conferred by Gerald Meyer, Assistant Chief of the Ground Water Branch, USGS, at the time. Theis was jokingly scornful of it and, in his introductory remarks, asserted that Meyer's future might be on Madison Avenue rather than in the Geological Survey.

problems (that is, someone specifically trained in applied mathematics). Meinzer said that they already had Lee Wenzel on the staff, whereupon Theis replied that Wenzel was a good man, but he was not a mathematician. Meinzer then asked why he wanted this "super-Einstein," and Theis briefly described the problems they were having determining aquifer characteristics on the High Plains.

Theis visited a mathematician who was working at the Helium Plant of the Bureau of Mines at Amarillo, an Englishman, to discuss the mathematical aspects of the non-equilibrium problem, but the meeting had no beneficial result, possibly because Theis had not completely worked out the conception of the problem in his head. He next spoke with a mathematician who was teaching at the college (now Eastern New Mexico University) at Portales, a Scotsman, but again, nothing came of the meeting.

On December 19, 1934, while still in Amarillo, Theis wrote to his old friend, Clarence Lubin, who was then teaching in the College of Engineering at the University of Cincinnati. Theis now had a clear idea of "the physical conception of the process," and he described the problem in detail to Lubin:

> The flow of ground water has many analogies to the flow of heat by conduction. We have exact analogies in ground water theory for thermal gradient, thermal conductivity, and specific heat. I think a close approach to the solution of some of our problems is probably already worked out in the theory of heat conduction. Is this problem in radial flow worked out? Given a plate of given constant thickness and with constant thermal characteristics at a uniform initial temperature to compute the temperatures throughout the plate at any time after the introduction of a sink kept at 0 temperature? And a more valuable one from our standpoint: Given the same plate under the same conditions to compute the temperatures after the introduction of a sink into which heat flows at a uniform rate? I forgot to say that the plate may be considered to have infinite areal extent.

During the first week of January 1935, while on his way to Washington, D.C., Theis visited Lubin in Cincinnati. Within a day or two after their conversation, Lubin had worked out the mathematics of the problem, based in great part on equations published in H.S. Carslaw's book, "Introduction to the Mathematical Theory of the Conduction of Heat in Solids" (1921). Lubin mailed the solution to Theis in Washington, and Theis spent that spring working on a paper that would relate the heat-flow equations to ground-water problems.

Theis sent a copy of his paper to Lubin on April 23, noting that he had just finished it and would have to present it in a few days before the Section of Hydrology of the American Geophysical Union. He offered coauthorship to Lubin when the paper was published, stating that "it could not have been written without you." In his reply on May 7, Lubin commented that "I would not want to appear as co-author, first because my part in it was very small, second because from the standpoint of mathematics the work is not of fundamental importance, i.e. to mathematicians the mathematical part is not significant."

Theis' paper appeared in the Transactions of the American Geophysical Union in 1935 under the title "The Relation Between the Lowering of the Piezometric Surface and the Rate and Duration of Discharge of a Well Using Ground-Water Storage." It would not be an exaggeration to state that the publication of this paper revolutionized the science of ground-water hydrology. The Theis paper provided a foundation for the application of well hydraulics to aquifer evaluation that would be used by hydrogeologists for decades to come.

In his 1935 paper, Theis twice acknowledged the contributions of Lubin and also referenced the equations published in Carslaw's book on the conduction of heat. He also acknowledged the assistance of Dr. C.E. Van Orstrand of the U.S. Geological Survey, and by so doing gave a hint of controversy that had arisen in the Survey regarding the work on the non-equilibrium problem. In spring 1935, while he was in Washington preparing his paper for publication, Theis was told that Van Orstrand had done some work on the non-equilibrium problem. When Theis went to see him, Van Orstrand pulled out a page or two with the problem worked out in terms of the exponential integral; however, Van Orstrand had abandoned the work because he could not figure out the "physical conception" of the problem. Theis concluded that after having described his work to Meinzer at the AAPG meeting in Dallas, either Meinzer or Wenzel had taken the problem to Van Orstrand.

The relationship between Meinzer and Theis was rather complex. Meinzer sponsored Theis for fellowship in the Geological Society of America, to which he was admitted in 1936. Meinzer was pleased with Theis' work on the High Plains, but he apparently was not convinced of the need (or validity) of the quantitative approach to the non-equilibrium problem. At Meinzer's request, Theis wrote a paper on his non-equilibrium work to be presented at the meeting of the Society of Economic Geology in Washington in December 1937. Meinzer accepted the paper but later returned it with a note that it had made a "very unfavorable impression" on several men at Geological Survey headquarters. However, Theis presented his report orally at the meeting in December 1937, and it was published in Economic Geology in December 1938.

In 1939, Theis presented a paper on "The Source of Water Derived from Wells" to the Arizona section of the American Society of Civil Engineers. Afterward, when asked to prepare the paper for publication, he protested that the same material had been published twice, but he was told that it should be published again so that his work would be brought to the attention of the engineering profession. As a consequence, his paper was published in Civil Engineering in May 1940. Thus, with publication in three prestigious journals in 5 years, Theis' ideas were given wide distribution, and the "Theis equation" was soon widely used in the analysis of aquifer characteristics.

Theis was appointed District Geologist of the Ground Water Branch in New Mexico in 1936. He and Gladys moved to Albuquerque and bought a home near the University of New Mexico. Gladys was achieving some fame with her sculpture. She had studied art at her home in Oklahoma, at the Cincinnati Art School, at the Corcoran School of Art in Washington, and in Paris; she was listed in the first issue of Who's Who in American Art (McGlaughlin, 1935) when it appeared in the mid-1930s. Theis and his wife adopted a baby girl in 1940; named Marilyn Ruth, the baby was a cousin of Gladys'. Theis and his wife are shown at about this time in figure 2.

Figure 2. C.V. and Gladys Theis on a field trip, Ouray, Colorado, 1940.

During the late 1930's, Theis continued his work in Lea County and in the Portales Valley, and he also undertook an investigation of the Mimbres Valley in southwestern New Mexico. What occupied most of his time, however, was the Rio Grande Joint Investigation, which was an intensive study of the river done in cooperation with other Federal agencies and the New Mexico State Engineer Office. Theis concentrated his efforts on the Middle Rio Grande Valley, from the mouth of White Rock Canyon in the north to San Marcial in the south.

In 1941, two or three weeks after the attack on Pearl Harbor, Theis received an inquiry from Washington regarding his availability for work at military bases in North Africa. He indicated by telegram his willingness to go, but sent a letter a few days later stating that his doctor would not certify him for duty in a hot climate. The reason given was that his body temperature was typically 1 or 2 degrees above normal on hot days, and his doctor thought that he would be subject to dangerously high fevers if he were to work in North Africa.

In September 1942, Meinzer wrote to Theis in Albuquerque asking if he would be willing to take charge of the ground-water work in the Military Geology Unit in Washington in the event that A.N. Sayre was detailed elsewhere. In February 1943, Sayre was scheduled to work in El Salvador and Ecuador for 2 months, and Theis was asked to go to Washington to take his place. In fact, the detail stretched to 5 months, and Theis worked in Washington well into that summer investigating water-supply problems at military bases.

Theis returned to Albuquerque, but in the autumn he was asked if he would be available for duty with the Corps of Engineers regarding water-supply problems associated with the construction of the Alaska Highway. He telegraphed his acceptance and on October 15, 1943, left for Canada. He worked all through the winter of 1943-44 in Alberta, British Columbia, and Yukon Territory, Canada, and in Alaska. Theis enjoyed saying that as a reward for spending one of the hottest summers on record in Washington, he was sent to Alaska for the winter. He wrote short reports about developing water supplies for military bases along the Alaska Highway, and he also turned his attention to permafrost problems. When he completed his work in late March 1944 and returned to Albuquerque, the Commanding General of the Northwest Service Command sent a letter to Washington commending Theis' "exceptional initiative and professional ability."

Theis resumed his duties as District Geologist in New Mexico. For about 3 years, however, beginning in the middle of 1945, he also spent part of his time doing research on mine drainage and the relation of ground water to ore deposits in the Iron River area in Michigan. During the late 1940's, he also spent part of his time considering water supply and radioactive-waste problems at the nuclear research (later Atomic Energy Commission) facility at Los Alamos, New Mexico.

In January 1951, Theis was asked to assume responsibility for coordinating all U.S. Geological Survey work for the Atomic Energy Commission (AEC). Theis accepted the offer, but only on the condition that the work be done out of Albuquerque; he expressed opposition to moving to Washington under any conditions. Clyde S. Conover took charge of Ground Water Branch activities in New Mexico when Theis began his new duties.

Reference was made earlier to Theis' election to fellowship in the Geological Society of America (GSA), and to his membership in the honorary engineering society, Tau Beta Pi. He had joined the American Geophysical Union in the early 1930's. He was also a member of the American Association for the Advancement of Science. His involvement in the affairs of these societies was, in general, nominal; but he read their scientific publications diligently, as evidenced by marginal notes in the copies in his personal library, and regularly made financial contributions to them. He was elected to the national chairmanship of the Hydrogeology Division, GSA, in 1968, having become affiliated with it upon its formation as a Division in 1959. He was a long-time member of the Rotary Club of Albuquerque, N. Mex., and gave as his reason for resigning, when he was in his mid-eighties, that he wished to make room in the club for new young members.

In March 1952, Theis was elected to membership in the Cosmos Club in Washington. He sometimes stayed there during his trips to Washington. In January 1972, he sent a letter of resignation stating that "it is unlikely that I shall have the opportunity to use the facilities of the Club again."

Theis' leadership of the work of the Geological Survey on behalf of the Atomic Energy Commission not only heightened his interest in problems of mass transport by ground water, but also led to his service on a committee established by the National Academy of Sciences/National Research Council (NAS/NRC) at the request of the AEC to advise on research and development related to ground disposal of radioactive wastes. The first meeting of a "steering committee" was held at Princeton, New Jersey, in September 1955; it was attended by a large number of distinguished earth scientists, including Theis and seven others from the USGS, and culminated in a report (NAS/NRC, 1957) that provided guidance for research on radioactive waste disposal for many years. Subsequently, the committee had several different names, and Theis became the sole representative from the USGS, serving until the early 1970's, when the committee underwent major changes in both membership and function.

Theis' role on this committee was somewhat unusual, if not unique. As a result of his coordination responsibilities for USGS work in support of AEC's mission, he had detailed knowledge and understanding of the geology and hydrology of the AEC facilities at which the projects being reviewed by the committee were carried out. The other members based their reviews on information provided by project personnel in advance of committee meetings and on information gained through oral presentations and brief field trips taken in the course of committee meetings. Theis tended to be rather quiet during some of the committee discussions—seemingly passive at times. But he often rose to the defense of AEC-supported scientists and engineers in opposition to criticism by other committee members, especially if he felt that the objectivity, integrity, or technical capabilities of the investigators were being questioned. His contributions to committee reports were often based on his own detailed and independent analysis of data collected in the course of research and development projects and, as such, commonly represented the most substantive and pragmatic parts of the committee reviews.

It was probably Theis' knowledge of the geology and hydrology of the AEC sites, as well his credibility as a spokesman thereon, that led to direct communication with such influential figures in the field of nuclear energy as Glenn T. Seaborg and Edward Teller. According to Bobbie Cloud (written commun., May 4, 1992) it was not unusual for Theis to get telephone calls from them that would last 30 minutes or more, and on one occasion Teller arrived at Theis' office unscheduled and unannounced for a lengthy conference on some topic of mutual interest.

In 1957, with the establishment of the Radiohydrology Section of the Water Resources Division in Washington, whose purpose was to coordinate work of the Geological Survey related to the occurrence of natural radioactivity and radioactive waste disposal with similar interests of the Atomic Energy Commission, Theis was reassigned to the Office of the Division Chief (although his duty station remained in Albuquerque) and was asked to do advanced research in hydrology. Much of his time was spent considering the hydrologic aspects of nuclear-energy research and development, but he also cooperated in the publication of a number of papers on new techniques in aquifer tests.

Beginning in September 1961, Theis took several months leave each year to initiate and teach a graduate course in ground-water geology at Columbia University in New York. He taught at Columbia during each autumn semester until 1964, but continued to have at least some of his secretarial work done in Albuquerque. It was during this period that he undertook to translate Schoeller's (1962) textbook, "Les Eaux Souterraines," from French into English; his tape-recorded translation was transcribed (with frequent reference to a French-English dictionary) by Bobbie Cloud, his secretary for many years. All through the mid-1960's, he was also a "faculty associate" in the geology department at the University of New Mexico; this position did not include regular teaching duties.

In 1965, when he was 65 years old, Theis received an appointment as a Division Scientist, and was asked to do "whatever research you consider to be most important in fulfilling the Division's current and long-range objectives." This charge was actually somewhat redundant, because C.V. Theis had been carrying out the charge, within the framework of his interests, talents, and assigned responsibilities, for many years. As usual, his best work was derived from problem solving—problems presented by areal or topical field studies—and the late-career contributions were no different.

Theis continued pursuing his interest in the role of geologic inhomogeneities and their consequent permeability contrasts in determining the fate of contaminants in ground water—their rate and direction of flow and concentration distribution. He had earlier devised a laboratory model built of glass beads, in which simulated lenses of higher hydraulic conductivity were embedded in a matrix of lower conductivity to demonstrate the effects of such inhomogeneities on the dispersal of constituents dissolved in ground water. The models were constructed and tests run in the Phoenix, Ariz., laboratories of the Water Resources Division, USGS, under the direction of and in collaboration with H.E. Skibitzke, using graded sands and epoxy resins. Skibitzke recalls (written commun., May 29, 1992):

> Once he asked me to construct a three-dimensional model to his specifications. In the upper layer, he wanted stripes of highly permeable materials at forty-five-degree angles [to the general direction of flow]; the middle layer was to be uniform; and the lower layer was to have stripes of the highly permeable material at forty-five-degree angles in the direction opposite to those of the upper layer, so that the intersections were overlaid. He predicted that the dye entering the model should take a spiral form as it flowed the length of the model. I assured him that that would be a contradiction to Laplacian flow. We made the model for him and the dye did indeed spiral. The results of these experiments were presented as part of several papers that Theis presented in the late 1960's.

Beginning with a paper presented in 1960 to a working group of the American Geophysical Union on ground-water research needs, Theis became something of an advocate for the overriding importance of geologic inhomogeneities on contaminant dispersion. He had studied the results of theoretical and laboratory investigations carefully—indeed, he had attempted to apply them to a field situation that required the siting of monitoring wells downgradient from a contaminant source and learned a hard lesson—and was seeking ways of characterizing the geologic factors involved. He had also become concerned that the success of mathematical models based on simplifying assumptions was constraining the thinking about the true characteristics of the real-world system. This evolution of his thinking demonstrated both his intellectual flexibility and the quality of his training and development as a geologist. Theis was fond of saying, with perhaps some hyperbole and considerable humor, that he had spent the first half of his career convincing students of ground-water hydrology of the validity of the non-equilibrium concept, and the last half trying to prevent the rape of his brainchild. His work on heterogeneity led to its characterization by Anderson (1989) as follows: "However, like other men and women of genius, he had an uncanny ability to foresee the problems that would be faced by future generations."

In 1965, Theis was asked to serve on a Committee on the Redefinition of Ground-Water Terms, chaired until 1968 by A.M. Piper and subsequently by S.W. Lohman. The other members were Water Resources Division colleagues, all well-respected ground-water scientists. The committee held meetings in Arizona in 1966, Colorado in 1969, and New Mexico in 1970; otherwise, business was carried out by mail and telephone. The discussion was opened with a memo dated November 30, 1965, from J.T. Callahan (Acting Chief, Ground Water Branch) suggesting 14 points for consideration by the committee. In his reply of January 7, 1966, Theis made some preliminary comments. As to the question of "whether recharge applies only to new water introduced to a system or applies equally to water entering an aquifer from other aquifers," Theis replied, "The point eludes me." With regard to the terms "effluent" and "influent" applied to streams, Theis suggested "dropping these confusing words as technical terms"—which was eventually done.

Although Theis suggested at one point during the lengthy exchange of correspondence that the term "aquifer" had probably outlived its usefulness and would gradually drop from usage, he continued to ponder the reasons for confusion in its usage. In the early 1980's, he began work on a paper that reconsidered the definition of aquifer and introduced a new term, "hydropher," which he restricted to the saturated part of an aquifer. The resulting paper is published in this volume.

In 1969, Theis began service on a committee to advise an investigation on the feasibility of artificially recharging the aquifer beneath the southern High Plains of West Texas and eastern New Mexico. The concept was to import water from the drainage basins of eastern Oklahoma and Texas for underground storage and use. The USGS project, headquartered at Lubbock, Tex., investigated the hydrologic implications of interim storage of the imported water in playa lakes and various aspects of infiltration of water from the surface to the water table. Theis' role on the advisory committee was more or less typical of his role on similar committees; he became intensely interested in the work and provided valuable scientific and technical assistance to the project team as well as general advice. According to Richmond F. Brown, chief of the recharge project at the time, Theis would arrive several days before committee meetings and often stay several days after them, working directly with team members. Brown characterized Theis' help as being the most useful of all the advice given by committee members. Theis' contribution to the project led to an analysis of the effects of infiltration from canals needed to deliver water to the project area, published as USGS Professional Paper 750-B in 1971 (R.F. Brown, oral commun., March 4, 1992).

Theis officially retired in 1970; his retirement party on April 10 was attended by friends and colleagues in the hydrologic profession from across the country. Retirement did not really change his schedule, however. He still went to the office every day and worked on scientific questions that attracted his attention, but judging from the volume of notes left in his office when he died, he must have spent considerable time working out mathematical puzzles, which held a strong fascination for him.

The question of aquifer anisotropy occupied Theis' attention in the early 1970's, and he lectured on this subject a number of times. He also prepared the manuscript, "A Primer on Anisotropy," used as a teaching aid to accompany those lectures, and first published in this volume. This paper was a direct outgrowth of his participation in the work of the ad hoc committee to revise ground-water nomenclature, referred to previously, but his view of the importance of the subject was derived from the broader experience with contaminant flow.

Throughout his long career, Theis' advice was sought on hydrologic problems by colleagues in the Geological Survey and by investigators of ground water worldwide. On some occasions the counseling was given as part of a field visit; on others it was given by correspondence. The correspondence, in particular that giving advice to younger hydrologists during the latter part of his career, is especially revealing of the man and his personality. The advice was always thorough, and usually compassionate and fatherly; only if the seeker had failed to define the problem under investigation adequately, or worse yet, had ignored data because it failed to fit a favored hypothesis, was it likely to be harsh.

Theis and his wife moved into a retirement home in 1981, and by the mid-1980's, his work schedule began to decrease. He began to come into the office only 4 days each week, and then 3 days. Only in the last 6 months of his life, when he required oxygen and was ill with emphysema and lung cancer, did he fail to show up at his office at the Water Resources Division in Albuquerque. Even during this time, however, he used a tape recorder to add to his autobiography and to make comments about some aspects of his earlier work that came to his attention. C.V. Theis died on July 31, 1987.

The number of honors bestowed on C.V. Theis by scientific colleagues and by scientific and professional organizations attests as much to his qualities as a human being as to his scientific accomplishments. In 1963, a "Symposium of Transient Ground Water Hydraulics," held at Colorado State University (Maasland and Bittinger, 1963), was dedicated to Theis. In 1966, a textbook "Hydrogeology" by Stanley L. Davis and Roger J.M. DeWiest was dedicated to Theis. He was designated the first honorary member of the American Water Resources Association and he held a similar position in the Ground Water Technical Division, National Water Well Association, since renamed the National Association of Ground-Water Scientists and Engineers. That organization dedicated a symposium on the "Geohydrology of the Dakota Aquifer" (see Hendrickson, 1984) to Theis; the proceedings volume includes a characterization of Theis by G.E. Hendrickson that accords high praise to his friend and former boss.

Hendrickson referred to a conversation with an associate several decades earlier on the occasion of Hendrickson's impending assignment to Theis' office in which the associate said, "Your new boss is a cold-blooded analyst." Hendrickson's remarks to the symposium averred, "An analyst he was and is, but cold blooded, never. Perhaps he seemed cold blooded to some because he was never a flatterer. If he praised your work, you could be sure you deserved this praise. And if he criticized your work, you knew that his intent was only to improve the work and never to disparage the person who produced it."

Fortunately and deservedly, many honors were bestowed during Theis' lifetime, such as the Horton Medal of the American Geophysical Union, referred to earlier. In 1987, the American Institute of Hydrology honored Theis by establishing an annual symposium dedicated to him, and in 1988, the symposium included accolades from colleagues, associates, and fellow scientists. The organization also established, and presents annually, the C.V. Theis award for an outstanding contribution in ground-water hydrology.

Many superlatives could be used in describing C.V. Theis' contributions to hydrology, but one of the best and most succinct assessments of his career was made by E.L. Hendricks, the Chief Hydrologist of the U.S. Geological Survey, in 1968:

> A senior scientist, having an international reputation for excellence in his chosen field of science and recognized by all of his associates as having no peers. Contribution to the Division's program & objectives is very great and much appreciated.

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Bibliography of C.V. Theis

Compiled by Alfred Clebsch

INTRODUCTION

This bibliography is an extension of a compilation of reports authored by Theis and maintained, until about 1980, by secretaries on his behalf as an administrative requirement of the U.S. Geological Survey, Water Resources Division. After 1980, when his secretarial help was minimal, Theis made several handwritten entries himself, and the compilation was thought to be accurate and complete; however, in the course of editing the bibliography and assembling copies of the publications in 1988, a number of omissions and one erroneous entry were discovered. It is believed that all the significant omissions from the earlier compilations have been included in this bibliography, but several titles are included for which copies have not been found. Some entries lack bibliographic details, and despite inquiries to a number of potential sources, copies have not been located. For at least one entry, all copies are believed to have been either lost or destroyed.

This introduction has been prepared in order to indicate the breadth of Theis' scientific interests and contributions; to show the relative productivity of different periods of his career; to give the location of some of his less well-known but significant writings; and to call attention to important contributions. It is intended also to suffice for annotations, although a few entries in the listing have been annotated to explain the sequence of preparation and revision or dual release. The introduction is not intended to be an exhaustive review or an evaluative commentary that would place Theis' contributions to hydrogeology in the context of the total body of literature on the subject.

Format and Availability

The compilation includes, in separate lists, (1) 121 publications and open-file reports for which Theis was the sole author; (2) 34 publications and open-file reports for which Theis was a coauthor, (3) 4 publications to which Theis made a contribution without authorship credit, except by acknowledgment; (4) 6 unpublished and unapproved manuscripts; and (5) 6 reports that could not be located, including those with incomplete citation data. The last group is taken in part from a card file in the Headquarters of the Water Resources Division; copies of the reports must have existed there at some time, but presumably were lost or discarded. The lists depart from the conventional USGS publication format in that Theis' authorship has been omitted, except where necessary to indicate the correct order of coauthors. The entries in each list are in chronological order.

Reports listed "Open-File Report" without a number may not be readily available except for the copies contained in the C.V. Theis Collection at the Center for Southwest Research, General Library, University of New Mexico (UNM), Albuquerque, New Mexico 87131. Reports about New Mexico also are in the files or library of the District Office of the Water Resources Division in Albuquerque. Numbered open-file reports are available from U.S. Geological Survey, Books and Open-File Reports Section, Box 25425, Denver Federal Center, Denver, Colorado, 80225-0425.

Some of the entries in the first and second lists were not formally released as open-file reports, but have been given such wide distribution within the USGS and among its State, Federal, and local cooperating agencies that they have achieved a *de facto* open-file status. The informal series of Ground-Water Notes represents a case in point, although most of the ones authored or coauthored by Theis were published later in slightly modified form in Water-Supply Papers 1536-I or 1545-C. Appropriate Ground-Water Notes are cross-referenced to the proper Water-Supply Paper, which is the more readily available source.

A number of Theis' reports that had been prepared at the request of the U.S. Army Corps of Engineers and other Federal agencies, mostly in the 1940's, were released in the open-file report series in 1991, with the approval of the cooperating agency, so they could be included in this compilation. Many of them had previously been designated "Official Use Only." Inclusion of these reports shows both the diversity and volume of Theis' writings on a variety of water-related problems, which frequently provided a foundation for other, more scientific work. The individual reports are listed in the order of their preparation rather than by the date of their formal release, as are several other reports that were written in the 1930's and 40's and released in the open-file series a number of years later. Such reports may be recognized by the open-file report number, which includes both the year and a number designating the sequence of open-file release in that year; for example Open-File Report 91-81. A number of Theis' reports were grouped together and released under the following titles: "Short papers on water supplies and engineering geology, Alaska Highway, 1943-1944," Open-File Report 91-80 (1991a); Theis and others, 1991, "Short papers on water resources in New Mexico, 1937-1957," Open-File Report 91-81; and "Potential hazards to water resources along a test-flight path, 1952; Possible disposal of liquid waste in a deep saline aquifer, 1954; and Hydrologic aspects of a proposed burial ground, 1965," Open-File Report 91-82 (1991b). In the lists, the title of the grouped reports has been omitted, in order to save space.

The Theis Collection at the University of New Mexico includes copies of the publications to which contributions were made without authorship credit. Theis' contributions to the reports of the National Academy of Sciences/National Research Council Committee on Geologic Aspects of Radioactive Waste Disposal are dispersed within the reports, which are most readily available from the successor agencies of the U.S. Atomic Energy Commission (AEC). USGS Bulletin 841 (Baker, 1933) is readily available in repository libraries for USGS publications. The Resource Survey of the Commercial Club of Cincinnati (Fenneman, 1927) probably had limited distribution.

Copies of the unpublished manuscripts and unapproved reports are in the Theis Collection at UNM. An example is the report by Theis, Burleigh, and Waite (1935). Although copies of some manuscript reports also may exist in the files of various USGS offices, a reader who wishes access to such a report should, in general, contact the Center for Southwest Research, UNM General Library.

The "Papers that could not be located and those with incomplete citations" might have fit into one of the previous categories if they could have been found. It seems likely that copies had been sent to USGS Headquarters, because that office was the source of the information listed. But the copies could have been discarded or destroyed at some time. Copies were not found in Theis' files, but no efforts were made to locate copies in the files of the agencies for whom the reports might have been written.

Although this bibliography includes many items that could be considered informal notes or memoranda, the Theis Collection contains several other manuscripts that might have been included, but have not for various reasons. Some notebook entries, either from the 1930's, or from the 1960's when Theis was an adjunct professor at Columbia University, although sufficiently well organized, well written, and thoughtful to have constituted a publishable paper at the time, have been omitted. One example is a 1930's essay on the need for a ground-water research laboratory. Other, more formal, manuscripts that have been omitted include an analysis of drawdown in the vicinity of well fields having different geometries; a colleague reviewer who was familiar with the European literature pointed out that a solution to the problem had already been published in Switzerland.

Other material exists that is of a personal nature. Several romantic poems written by Theis in the late 1920's relate to the environment and circumstances of meeting his future wife. Several years before his death, Theis began writing his autobiography, but it covered only the period to the mid-1940's. Just a few weeks prior to his death, he dictated impressions and recollections of professors and colleagues at the University of Cincinnati and at Columbia University. These writings are not listed, but the autobiography was a major source of information in the biographical sketch included in this volume.

Publications in Seven Decades

The time span of Theis' scientific output is remarkable in itself. Although an entry in the Bibliography of North American Geology credits him with a geologic map of Hopkins County, Kentucky, published in 1924, Theis noted on his own compilation of publications that he was responsible only for the drafting, the mapping having been done by L.C. Glenn, later professor of geology at Vanderbilt University. Nevertheless, Theis' first publications were geologic maps resulting from summer work with the Kentucky Geological Survey during the 1920's.

Although Theis' reputation as a scientist is based primarily on his contributions to ground-water hydrology, his first publication with quantitative or mathematical connotations was his paper on evaporation (1931). The bibliography also illustrates a geographically wide range of hydrologic problem solving, mostly involving water supplies, but including engineering geology related to dam construction (1936b) as well. The report on south-central

Tennessee (1936a) documented Theis' first field assignment with the USGS. Reports on areas or sites in Oklahoma (1934a) and Arizona (1938f) typify the kind of studies that were to occupy this and the next decade.

During the 1930's, Theis published 32 titles and completed the unpublished manuscript on the southern High Plains with Burleigh and Waite. Theis' most widely recognized publication (1935b) evolved from an areal investigation in east-central New Mexico (1934d), and his interest in the southern High Plains gave rise to the analysis of some of its hydrogeologic problems. That interest would result in publications for another 40 years. Theis' approach to estimating annual recharge in the southern High Plains (1937a) was unique; it attracted wide attention in the Southwest because it was so fundamentally sound and provided a quantitative estimate of an essential hydrologic characteristic that is frustratingly difficult to determine, or even estimate, in arid and semi-arid environments. His analysis of fluctuations of ground-water levels in response to earth tides (1939e) was the first recognition of the hydrologic significance of earth tides in the American literature.

With the advent of World War II, Theis' energies were focussed on development of water supplies for military bases and other war-related needs in New Mexico, but the more noteworthy publications of the early 1940's resulted from his effort to extend the use of the non-equilibrium concept to the engineering community (1940) and to stream-aquifer relations (1941b).

Theis worked for several months with the Military Geology Unit of the USGS in Washington in 1943, but apparently no citable reports came from the assignment. He worked in Alaska and Canada during the winter of 1943-44 on water supplies and engineering geology in connection with facilities along the Alaska Highway and produced a large number of reports written for the U.S. Army Corps of Engineers. These reports were released to the open file in 1991 in preparation for listing in this bibliography. The Alaska highway work led to the preparation of "Thermal Processes Related to the Formation of Permafrost" (1944a). It is unfortunate that the paper was not distributed more widely, either in the open-file series or by publication, because at the time, the ideas represented a significant contribution to the understanding of permafrost. Theis applied his knowledge of heat flow to the question of the origin of permafrost, and his reasoning not only helped put to rest the notion that permafrost was a relict phenomenon from the Pleistocene, but it also demonstrated that the climatic conditions that control the occurrence of permafrost are highly site dependent, and variations in snow cover, both seasonally and from year to year, have profound effects on the formation and persistence of permafrost. One of the more significant findings in the paper was that late-season snowfall after a very cold winter could, by providing insulation during the early spring warm-up period, enable permafrost to form in areas where the mean annual air temperature was higher than zero degrees Celsius. This analysis helped to rationalize the presence of a number of permafrost occurrences in regions where the mean annual air temperature was above the freezing point of water.

Theis' thermal analysis of permafrost in relation to climatic, vegetative, and geologic factors was one of the first efforts outside the Soviet Union to apply engineering physics to the problem, but for reasons that are unclear, this noteworthy effort received little attention. The paper was cited in permafrost literature as an unpublished manuscript a few years after it was written, and wider distribution might have resulted in a greater stimulus to permafrost research at the time. In the tremendous expansion of permafrost research that accompanied the growth of the Cold War, the work was superseded, but at the time, Theis' paper "* * *would have been in a class by itself." (A.H. Lachenbruch, USGS, written commun., February 6, 1990).

Beginning in mid-1945, Theis worked on problems of mine drainage in the Iron River mining district of northern Michigan, the results of which were published by the Michigan Geological Survey (Stuart, Theis, and Stanley, 1948). Yet another example of a more fundamental study as an outgrowth of work to solve a specific problem is the unpublished manuscript (1945) entitled "The Nature of the Hydraulic System Involved in the Enrichment of Iron Ore near Iron River, Michigan." Marginal notes in the manuscript indicate that it was reviewed by at least one colleague, and other notes in Theis' handwriting are critical of some aspects of the manuscript. There is no evidence that the paper was proposed for publication, but it is a prime example of the fertility of Theis' scientific thinking.

By the early 1950's, Theis was heavily involved in overseeing the work of the USGS for the U.S. Atomic Energy Commission (AEC); his first report on water supplies for Los Alamos, written in 1943 before there was an AEC, is euphemistically entitled "Preliminary Memorandum on Possibilities of Obtaining a Large Ground-Water Supply near Santa Fe and Socorro, New Mexico." No copies of this four-page report could be found, but a copy of a letter Theis wrote in response to a request for it indicates that the title was a "cover" for Los Alamos. His experience with hydrologic problems at Los Alamos, and undoubtedly his broad outlook and thorough approach to hydrologic problem solving, must have led to his role in providing technical leadership and coordination of water-supply and waste-disposal investigations at AEC sites and in the topical research of the USGS supported by AEC.

Even though much of his time was devoted to advising and supervising, Theis wrote a dozen reports in the 1950's related to water supplies and the disposal of radioactive wastes at AEC sites. This list included a paper presented at the 1955 United Nations Geneva Conference on Peaceful Uses of Atomic Energy (1956a), which reviewed the state of knowledge in the United States at the time on ground disposal of nuclear wastes, presented from an earth-science perspective.

Perhaps of most significance during the 1950's and 1960's was Theis' growing realization that the idealized model of a granular aquifer that had been so useful in developing well hydraulics was woefully deficient when applied to problems of mass transport. He first outlined his ideas on the role of permeability contrasts in the dispersal of contaminants in a talk (1961) presented at a meeting on ground-water research needs, sponsored by the American Geophysical Union, in Portland, Oreg. These ideas were developed and expanded upon over the next few years (1962a, 1963a, and 1967) as experiments conducted in the Phoenix, Ariz., laboratories of the Water Resources Division, demonstrated through the use of physical models that flow lines are "refracted" when they enter and exit zones of differing permeability.

During the 1960's, a number of papers related to well hydraulics were published that had been written by Theis as notebook entries a decade or more earlier. These notes were later refined or augmented by others for release in the Ground-Water Notes series, referred to earlier, for training and use by ground-water hydrologists in the use of well hydraulics to estimate aquifer characteristics. Russel H. Brown (oral commun., August 27, 1991), a coauthor of several of the papers, characterizes Theis as "very magnanimous" in granting coauthorship for his efforts. Water-Supply Papers 1536-I (Theis and Brown, 1954; Theis, Brown, and Meyer, 1954) and 1545-C (1963 b, c, and d; Theis and Brown, 1963; Theis and Conover, 1963) are published versions. Some of these published versions contain changes that were not submitted to Theis for approval prior to final publication, thus provoking scornful handwritten comments in Theis' copy of the book; he felt that the compiler had not fully understood the material and had changed the meaning. Also in the 1960's, reports on water-supply problems at various New Mexico sites, which were written by Theis and others in the 1940's and early 1950's, were being published in the 16th and 17th Biennial Reports of the State Engineer of New Mexico. Although the reports had met their original objectives as somewhat less formal releases, the basic information was considered to be more widely applicable and sufficiently useful to warrant more formal publication.

In the late 1960's, Theis participated in a committee effort to refine ground-water terminology (Lohman and others, 1972). The voluminous correspondence generated by committee members attests to the spirited debates that resulted in the publication of Water-Supply Paper 1988, and indicates the importance that Theis' clarity of thought and articulate expression had in the effort.

Theis' work in the early 1970's, after his formal retirement from the USGS, produced a draft of "A Primer on Anisotropy," which is included in this Water-Supply Paper; this was his last rigorous analytical contribution to ground-water hydrology and was an outgrowth of his participation in training activities of the USGS that related to the transport of contaminants in ground water. His interest in terminology and his lingering concerns that the committee report to redefine ground-water terms had not completely met its objectives resulted in his writing, in the early 1980's, the tract on "Aquifers, Ground-Water Bodies, and Hydrophers", also part of this Water-Supply Paper. Not surprisingly, several of Theis' last publications were written at the invitation of an editor or friend. The article, "Ground Water as a Mineral Resource" (1973) was written at the request of his long-time close friend, Charles Behre. The foreword to a planned Ground Water Handbook (1982) was requested by the editors of the volume, but apparently the effort has been abandoned. Theis' contribution to "Two Hundred Years of Hydrogeology in the United States" (1986) was likewise an honorary matter.

Acknowledgments

Compilation of this bibliography and the location and assembly of copies of the papers have been aided by many individuals. The efforts of Eugene R. Hampton and his coworkers in obtaining the approval of other Federal agencies and in retyping the large number of reports on water supplies and engineering geology written by Theis mostly in the 1940's were especially noteworthy. Copies of somewhat obscure reports were provided by John S. Havens, Oklahoma City, Okla.; James F. Wilson, Cheyenne, Wyo.; and Daniel P. Bauer, Rolla, Mo. A. Ivan Johnson saved several unpublished papers that were about to be discarded from the files in Reston, Va., some of which had been listed, but were not available elsewhere; others allowed the addition of a few titles to the list.

Numerous other individuals searched for missing items without success. All these efforts are acknowledged with sincere thanks.

Cynthia J. Shattuck, Albuquerque, N. Mex., entered an early draft of the bibliography into the computer, thus facilitating subsequent additions and editorial changes. Editorial review by Martha A. Crawford resulted in the correction of many errors, and improved the presentation and clarity. Their contributions are deeply appreciated.

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