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

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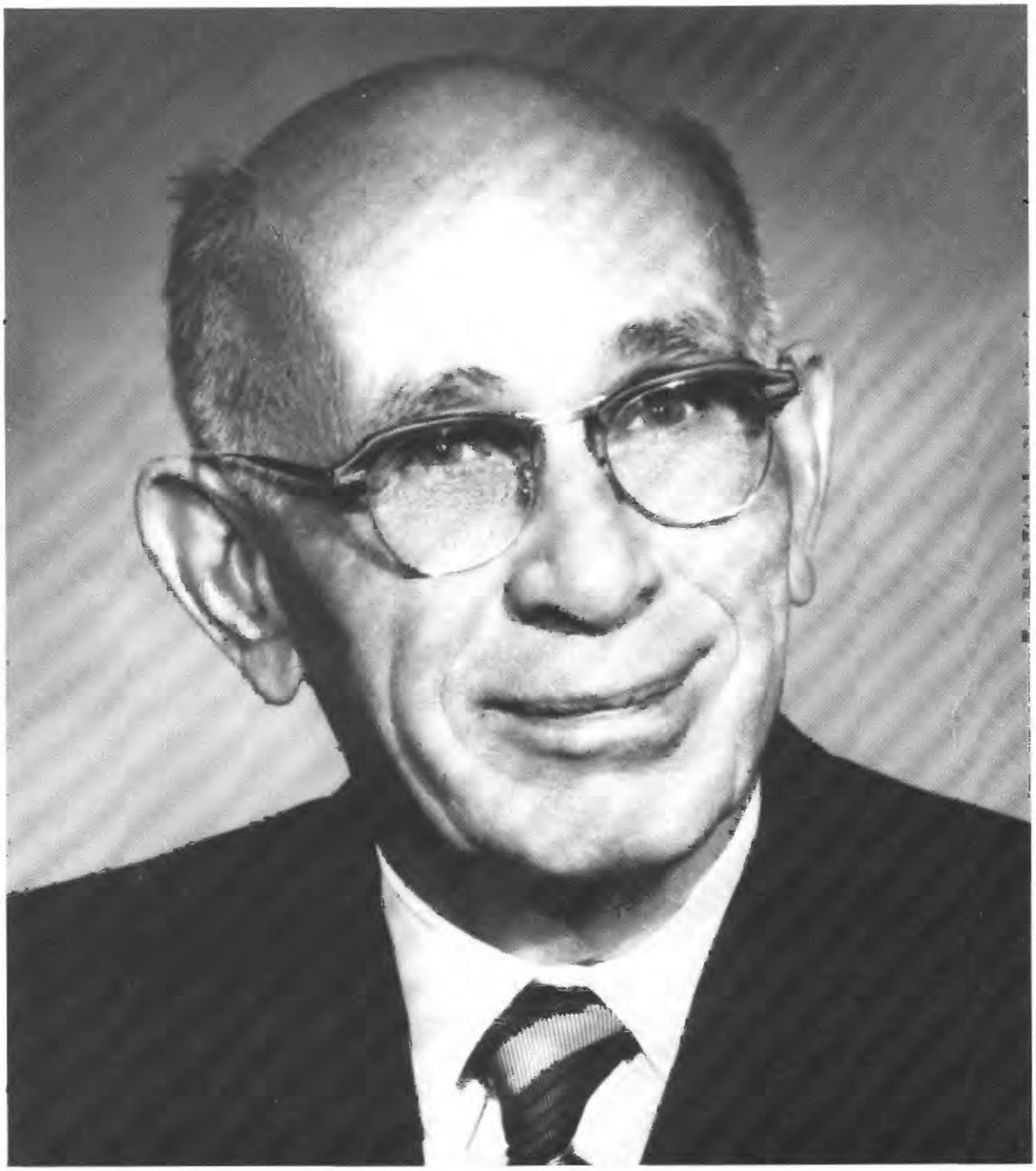

CHARLES V. THEIS

1900-1987

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 symplifying 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.

REFERENCES CITED

Anderson, Mary P., 1989, C.V. Theis and Heterogeneity, *in* Moore, J.E., Zaporozec, A.A., Csallany. S.C., and Varney, T.C., eds., Recent advances in ground-water hydrology, First C.V. Theis Symposium: American Institute of Hydrology, p. xix-xxi.

Carslaw, H.S., 1921, Introduction to the mathematical theory of the conduction of heat in solids (2d ed.): London, Macmillan, 268 p.

Davis, S.N., and DeWiest, R.J.M., 1966, Hydrogeology: New York, John Wiley, 463 p.

Hendrickson, G.E., 1984, Dedication of the first C.V. Theis Conference on geohydrology, *in* Jorgenson, D.G., and Signor, D.C., eds., Geohydrology of the Dakota Aquifer: National Water Well Association, p. 2-3.

Maasland, D.E.L, and Bittinger, M.W., 1963, eds., Transient Ground-Water Hydraulics Symposium, Fort Collins, Colo., December 1963, Proceedings: Colorado State University, Civil Engineering Section, 223 p.

McGlauflin, Alice Coe, 1935, Who's who in American art: Washington, D.C., The American Federation of Arts, 1936-37 (sic), v. 1, p. 419-420.

National Academy of Sciences/National Research Council, 1957, The disposal of radioactive waste on land: Washington, D.C., Publication 519, 142 p.

Schoeller, Henri, 1962, Les eaux souterraines: Masson et Cie., 120 Boulevard Saint-Germain, Paris, 642 p.