Sixth Annual New Mexico Water Conference

November 1-2, 1961

GROUND WATER

Availability

Quantity

Quality

Uses

New Mexico State University
Milton Student Center

University Park, New Mexico

NEW MEXICO WATER CONFERENCE

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Left to Right: Dr. R. B. Corbett, President, New Mexico State University; Dr. P. J. Leyendecker, Dean, College of Agriculture and Home Economics and Director of Extension Service and Experiment Station, N.M.S.U. chat with Governor Edwin L. Mechem. Governor Mechem was speaker at the Annual Water Conference banquet.

The Governor, Edwin L. Mechem, appears interested in sampling a part of the smorgasbord prepared for the banquet by Mr. Ed Rapp and his efficient student assistants at Milton Student Center. With him is Mr. Sanford Caudill, Manager of Arch-Hurley Conservancy District, left, and Charles C. Royall from the State Land Commissioner's Office, Phoenix, Arizona, right.

ATTENDANCE

SIXTH ANNUAL NEW MEXICO WATER CONFERENCE

by

Classification of Occupation or Major Interest

There has been considerable interest in knowing how wide the interested groups are that attend the Annual Water Conference. The following is a rough classification of those who registered during the Sixth Annual Conference. An undetermined, but rather large number of additional persons attended one or more sections of the conference, but did not register.

Governor	1
Engineers - Civil, Chemical, General	32
Agricultural Engineers	9
Hydraulic Engineers	3
Farmers and Ranchers	19
Irrigation Water Management	9
Foresters	5
Conservationists - Soils, Soil Conservation	5
Land Examiners	8
Agricultural Credit	5
City Water - Managerial	5
Industrial Representatives	8
Hydrologists	3
Geologists	12
Planning	5
Economists	5
Director - Administrators	5
Editors	2
Lawyers	6
Extension Service	6
Experiment Station - New Mexico	6
Colorado	3
Texas	1
Highway	1
Fish and Wildlife	3
Students	25
Wives attending with husbands who registered	11
TOTAL REGISTERED	203

FOREWORD

Ground Water was the subject of the Sixth Annual New Mexico Water Conference.

It is estimated that 90 percent of the water for industrial and municipal uses in New Mexico comes from ground water and that 587,000 of the 873,000 acres of the irrigated land in the State either are irrigated solely be ground water or have supplemental irrigation from ground water. These statistics indicate the vital importance of this subject to the people of New Mexico.

The papers presented in the conference helped to clarify many of the problems in connection with ground water exploration and development. The papers included "The Role of Ground Water in the United States," "Availability of Ground Water in New Mexico," "Changes in Quantity of Ground Water," "Economics of Ground Water Irrigation," "Quality of Ground Water--Changes and Problems," and "Ground Water Administration." Slides, films, special exhibits, and a special discussion on "Technical Problems" rounded out the program.

Consideration was given in these papers to the quantities and qualities of water required in industrial, municipal, recreational, and agricultural uses.

The conferences are open to every interested person and are designed to permit free and constructive consideration of how our New Mexico water resources can be conserved and developed. Milton Student Center on New Mexico State University campus has been the site of each of the past six conferences.

On the opposite page is given a list of those registered for the conference by general fields of interest. This listing reveals the extremely wide interest which is evident in the water problems in New Mexico and the Southwest. Although most of those attending were from New Mexico, the states of Arizona, Florida, Texas, Oklahoma, Colorado, Kansas, and California were represented.

The Water Conferences are sponsored by New Mexico State University through the Agricultural Experiment Station, Agricultural Extension Service, College of Agriculture, College of Engineering, and Cooperative Agencies of USDA-Agricultural Research Service, and Soil Conservation Service, with the cooperation of the Water Conference Advisory Committee and the New Mexico Department of Development.

The papers appearing in this publication are in the order in which they were presented. The program which follows this statement will serve as an index to the papers.

H. R. Stucky

H. R. Stucky, Head
Department of Agricultural Economics
and General Chairman of New Mexico
Water Conference

NEW MEXICO WATER CONFERENCE

New Mexico State University
November 1 - 2, 1961

THEME OF CONFERENCE - "GROUND WATER"

THE ROLE OF GROUND WATER IN THE UNITED STATES

O. M. Hackett[1/]

A conference may be defined as a meeting for an interchange of views, and it is with this definition in mind that I come to join you. For, in preparing this talk, it soon became evident to me that most of you in the Southwest are rather intimately acquainted with the ground-water resource, you have first-hand knowledge of many of the problems associated with its development, and you doubtless are as concerned with its wise management as is any similar group anywhere in the country. And so, I look forward not only to addressing you on a subject vital to all of us but, in turn, learning from you during this interchange of views today and tomorrow.

No doubt most of you are acquainted with the recently completed survey of the Nation's posture in the field of water by the Senate Select Committee on National Water Resources. The Committee's studies indicate that, if present trends continue, our demand for water, now on the order of 300 bgd (billion gallons per day), will increase by 1980 to 559 bgd, equivalent to 51 percent of average streamflow, and by 2000 to 888 bgd, or 81 percent of streamflow (U.S. Senate Select Committee on National Water Resources, 1961, p. 5). Because much of the water represented by the demand figures is returned to the streams and is available for reuse, these figures are not as frightening as they seem at first glance. Nevertheless, as a Nation we clearly face a serious water-supply problem. Already there are substantial areas of continuing water shortage in many of our western river basins. According to the Committee, full development of all the available water resources will be necessary by 1980 in 5 of the 22 water-resource regions if the projected increases in demand are to be met (idem, p. 9-11). These are the South Pacific, Colorado River, Great Basin, Upper Rio Grande-Pecos River, and Upper Missouri River regions. Of cource, the occasional water shortages that plague nearly all parts of the country are well known to all of us.

Are we going to be able to double our present supply by 1980 and triple it in less than 40 years to meet the predicted needs? Are we going to be able to balance regional supply and demand in a way that will be tolerable to us? And are we going to be able to eliminate or reduce in intensity the occasional water shortages that now plague us in most parts of the country?

1/ Chief, Ground Water Branch, Water Resources Divison, U.S. Geological Survey, Washington, D.C.

If we are to do so, there are two avenues we can consider: first, to add to our total water supply, and second, to make the most of what we have. If we had Aladdin's lamp today, we could simply rub the lamp, bring forth the genie, ask him to create for us the needed water supply, and so solve our problem. Science and technology are, indeed, a sort of Aladdin's lamp, and they hold forth the promise that by such techniques as desalting ocean water, purifying brackish water, modifying the weather, reducing evapotranspiration, and so on, we, in fact, may someday increase our total usable water supply. However, fulfillment of these promises is in the future--we cannot say when--and in the meantime our problems multiply.

Fortunately, the Nation as a whole is blessed with a bountiful supply of water. Our average runoff, which represents the upper limit of our manageable supply, is about 1,200 billion gallons daily (Langbein and others, 1949, p. 6). If we make the most of what we have--by maintaining the quality of the water to permit reuse, by routing it from areas of surplus to areas of deficiency, and by storing it at times of surplus to use at times of deficiency--we need not suffer for lack of water. In this direction much has been done, but much more remains to be done.

And this brings us to the theme of the conference--ground water. Ground water is difficult to define, difficult to describe, and difficult to comprehend. It is hidden and it cannot be measured directly. It is expensive to evaluate and difficult to manage (McGuinness, 1960, p. 9). Furthermore, its development often is accompanied by or followed by consequential problems that are difficult to predict and ofttimes costly to resolve.

Yet we have progressed far during the past decade or two, both in understanding ground water and in applying our knowledge to its development, use, and management. In general, we know the locations of our principal aquifers; we know the ground-water storage is enormous; and we know that recharge is substantial. We know something of the interrelation between ground water and surface water, and we have learned much about artificial recharge. We have developed test methods by which we can evaluate the hydrologic properties of our aquifers, and recently we have developed analog models which enable us to predict aquifer response to outside forces with a reliability limited only by the accuracy of the data used in setting up the models.

Also, during the past decade or two our use of ground water has increased greatly. In 1960 the total estimated withdrawal of ground water in the conterminous United States for all uses except hydropower was about 46 bgd (MacKichan and Kammerer, in press). Among the States, Texas was second in the use of ground water, Arizona third, and New Mexico ninth. Together these States pumped more than one-fourth of the total ground water used in the Nation.

The largest withdrawal of ground water was for irrigation--about 30 bgd. Arizona pumped 3 bgd, New Mexico 0.9 bgd, and Texas 7.7 bgd. More than one-third of the total for irrigation was pumped in these three States.

Industry supplied for its own use, including fuel-electric power generation, about 7 bgd. The largest withdrawals were in the East, but Arizona, New Mexico, and Texas together pumped 0.9 bgd--a substantial amount.

Ground water for public supply amounted to about 6 bgd, distributed roughly according to population. Among the States, Texas was the second largest user.

Rural use of ground water was only about 3 bgd, but this constituted most of the water derived for rural use from all sources. Altogether, in 1960 ground-water sources supplied about 1 in every 5 gallons of water withdrawn from all sources for all uses in the United States except waterpower.

The use of ground water has not been without problems, of which overdraft accompanied by increased pumping lifts and lowered yields, salt-water encroachment (not only in coastal areas but at some places inland as well), depletion of streamflow, and land subsidence are but a few. I could cite numerous specific examples, but I suspect that to you of the Southwest such examples are commonplace.

Now to the main purpose of this discussion--the role of ground water in helping us make the most of our water resources.

The first point I wish to emphasize is that ground water is not a separate and distinct resource. Rather it is a convenient term by which we distinguish water as it passes through or lingers in one part of the hydrologic environment from water as it passes through other parts of the environment. Except as, for a time, they can produce water that has accumulated over periods of many years, ground water reservoirs can add little to our total supply.

I do not mean to imply that the reserve stored in ground-water reservoirs is either small or unimportant. It has been estimated that the volume of ground water in storage in the United States above a depth of 2,500 feet is about 200 billion acre feet--equivalent to the total of all recharge during the last 160 years (Nace, 1958, p. 4-6). The stored reserve is enormous, and in places like the High Plains of Texas and some of the arid basins of the Southwest, where recharge is small, mining of this reserve has been a principal factor in developing and supporting the economy. Mining of ground water will continue to be important, but it offers no permanent solution to our water-supply problem. In the long run we must either furnish alternative sources of water for these areas of mining or change the character of the economy.

It is essential, therefore, that we do not permit the thought of ground water as a unique resource to dominate our thinking. Rather, we should emphasize the concept of aquifers as storage and distribution media, to be used as such either alone or in conjunction with streams and surface reservoirs. In this context our aquifers constitute a powerful management mechanism, which if fully employed should indeed help us to make the most of our water supply. Perhaps a few examples will illustrate the sort of uses I have in mind.

The Gallatin Valley in Montana is similar in many respects to many of the valleys in the Southwest. It occupies an intermontane basin in the Northern Rocky Mountain region. The valley floor is underlain by permeable alluvial deposits which form a large ground-water reservoir. Higher land along the sides of the valley is underlain by Tertiary strata of low permeability.

The climate of the valley is semiarid, but the Gallatin River, which flows across the valley, provides a source of water for irrigation. Because it is close to the river the land of the valley floor was irrigated first, and most of the earlier rights to use of water from the river are held in this area. Some of the later water rights permit irrigation of parts of the higher lands, but much of this area must be dry farmed. Land at the lower end of the valley floor is waterlogged and therefore is used mostly for pasture or forage crops.

Except for a reservoir on one of the small tributaries of the Gallatin River, there are no surface storage facilities. During the summer the river may be diverted completely, and water shortages are common for the lands irrigated under the later water rights.

Study of the Gallatin Valley (Hackett and others, 1960) suggests that the Gallatin River, its tributaries, a network of irrigation canals, and the ground-water reservoir could be managed together as a hydrologic system, utilizing the ground-water reservoir as the storage component. For instance, pumping of ground water for irrigation of the valley floor would permit some of the water from the river to be diverted for use on the higher lands along the sides of the valley. The spreading of water there would in turn provide recharge to the ground water-reservoir. And, the ground-water reservoir is in a position to intercept all return flow to the river. The discharge of the river during the winter and spring months is large enough to assure replenishment of the ground-water reservoir each year. It is possible that pumping from the ground-water reservoir might be useful also as a measure for controlling the waterlogging at the lower end of the valley.

An example from another part of the country is the valley of the Mattapoisett River, a short coastal stream which drains about 24 square miles in Massachusetts. Here the hydrologic system is a "watercourse" as that term is used by Thomas (1952, p. 10), consisting of the river and a closely associated ground-water reservoir.

In Massachusetts the annual runoff even during a dry year is relatively large and the potential water supply from even a small area is correspondingly large. During the summer months, however, the flow of a small stream such as the Mattapoisett sometimes becomes very low, and the water supply that can be sustained directly from the stream is limited accordingly. The ground-water reservoir consists of permeable glacial drift that partly fills a narrow preglacial valley in the impermeable bedrock of the area. The ground-water reservoir has a small storage capacity and can sustain large withdrawals for only a few months at a time.

In this situation the maximum yield from the annual water crop is possible only if the watercourse system is developed as a unit (Shaw and Petersen, 1960, p. 19-23). By placement of wells along the stream so as to induce infiltration from the stream, the stream can be utilized as a medium to collect water and in effect distribute it to the wells during the months when runoff is high. Then during the summer months when the runoff ordinarily is low, the ground-water reservoir can be utilized as a storage medium to sustain the withdrawals from the wells.

In many areas we do utilize our aquifers as storage and distribution media, and public authorities increasingly accept the need for developing an entire aquifer as a single unit. Nevertheless, the planned use of aquifers as components of larger hydrologic systems has been largely overlooked or neglected. With few exceptions, the planned use of aquifers as storage and distribution media has been neglected in the schemes for major river-basin developments.

We should remember that optimum use of aquifers as parts of larger hydrologic systems carries a price. We need first to identify and select the systems best suited to our purposes. We need, then, to analyze these systems in a manner that will yield us the widest choice of alternative measures for development and management and enable us to foresee the varied effects of development. Hydrologic data of all types are required. Many data are on hand but many remain to be gathered. In particular, data for aquifer description--suitable for use in setting up analog models--need to be gathered, and these data are especially expensive. Required also is research aimed at improving methods of analyzing hydrologic systems and at developing and testing methods of managing them.

We should remember too that time is of the essence, for as our demands grow and the stage of resources development approaches maturity we lose our freedom of action. We can either hasten to gather the facts and accelerate the research so that we may have a choice of alternatives and an opportunity to select the most palatable of the consequences, or delay until we have no choice but to react to the situation and accept the unplanned consequences.

We should bear in mind that preservation of the quality of the water as it passes through our aquifers is essential if they are to yield full value as tools to stretch our water supply. The problem of pollution of streams is well known and the need for corrective measures is generally accepted. We cannot permit deterioration of the water in our aquifers to become a problem on the same scale because remedial action may be effective only after a period of many years. Thus, constant vigilance, and prevention rather than cure, should be the order of the day.

We should bear in mind, too, that most problems are a natural consequence of the use of resources. We cannot avoid all problems, nor can we wave the magic wand and make them vanish. We can, however, by planning carefully and with full knowledge of the alternatives open to us, develop our water resources in such a way as to avoid or alleviate some of the more serious problems.

In summary, if we make the most of what we have--by reuse, routing, and storing our water supply and protecting the quality of our water from deterioration--we need not lack for water for some time to come. The vital role of aquifers in this scheme is as storage and distribution media to be used either alone or in conjunction with streams and surface reservoirs as parts of larger hydrologic systems. Let us collect the facts and do the research now, so that we may have the widest possible choice of alternatives in developing and managing the resources.

SELECTED REFERENCES

HACKETT, O. M., VISHER, F. N., McMURTREY, R. G. and STEINHILBER, W. L., 1960, Geology and ground-water resources of the Gallatin Valley, Gallatin County, Montana: U.S. Geol. Survey Water-Supply Paper 1482, 282 p.

LANGBEIN, W. B., and others, Annual runoff in the United States: U.S. Geol. Survey Circ. 52, 14 p.

MacKICHAN, K. A. and KAMMERER, J. C., in press, Estimated use of water in the United States, 1960: U.S. Geol. Survey Circ. 456, in press.

McGUINNESS, C. L., 1960, Ground water--A mixed blessing: Internat. Geol. Cong., 21st, Copenhagen 1960, Rept., pt. 20, p. 7-16.

NACE, R. L., 1958, Water management, agriculture, and ground-water supplies: U.S. Geol. Survey open-file report, 23 p.

SHAW, C. E., and PETERSEN, R. G., 1960, Ground-water conditions in the Mattapoisett River basin, Massachusetts: Commonwealth of Massachusetts Special Report on Ground Water Resources in the Mattapoisett River Valley, Bull. WR 1, p. 9-25.

THOMAS, H. E., 1952, Ground-water regions of the United States--their storage facilities: U.S. Cong., House Interior and Insular Affairs Comm., The physical and economic foundation of natural resources, v. 3, 78 p.

U.S. SENATE SELECT COMMITTEE ON NATIONAL WATER RESOURCES, 1961, National water resources: U.S. 87th Cong., 1st sess., Sen. Rept. 29, 147 p.

AVAILABILITY OF GROUND WATER IN NEW MEXICO

William E. Hale[1]

ABSTRACT

Large supplies of ground water, of a quality that can be used now, exist in sand and gravel aquifers principally in the southeastern and southwestern part of the State, in the Rio Grande Valley, and smaller supplies are available in the alluvium of most valleys. Aquifers in limestone predominate in the south-central part of the State and in the Grants area where moderate to large supplies of water can be developed. Sandstone aquifers capable of yielding small to moderate supplies of water occur primarily in the northeastern and northwestern part of the State.

The depth to water in much of the area at the lower elevations in the State is less than 200 feet. At higher elevations underlain by limestone and sand and gravel, the depth to water is more than 1,000 feet.

Supplies of water containing less than 1,000 parts per million are scarce in a large part of the Tularosa Basin, the Pecos Valley, and parts of northeastern and northwestern New Mexico.

INTRODUCTION

The discussion of the availability of ground water, as used in this paper, is separated into three categories: 1) where useable ground waters exist in New Mexico; 2) the depth to these waters; and 3) the amount of water that can be developed in places by single wells. Availability might be treated from several other points of view. The quantitative aspects of the supply--that is, how long a supply will last--is discussed in a paper by Mr. J. C. Yates of the New Mexico State Engineer Office. The availability of ground water of a specific quality required for various uses is discussed in a paper by Mr. J. M. Stow of the U.S. Geological Survey. The economic and administrative aspects of availability are treated in other papers.

Information on the areal occurrence of ground water, the depth to water, and yield of water-bearing beds is obtained by qualitative areal studies. "Qualitative studies" are here used in contrast to quantitative studies, and do not refer to

1/ District Engineer, Ground Water Branch, U.S. Geological Survey, Albuquerque, New Mexico.

the quality of the ground water as such--although quality of water is an important phase of qualitative studies. Qualitative areal studies of various parts of New Mexico have been made by the U.S. Geological Survey in cooperation with Municipal, State, and Federal Agencies for many years. This paper presents general information, and some purely speculative comments, on the availability of ground water in New Mexico gleaned from these joint studies and from reports of State and other Federal Agencies.

Geology is a most important factor in the occurrence of ground water because the type, extent, thickness, and attitude of the rocks determine, to a great extent, the yield and quality of water that can be developed at a particular site. Precipitation, of course, is needed to supply the water that is in the rocks. Sand and gravel, limestone, and sandstone are the most important water-bearing rocks in the State; ricks of igneous origin contain and yield useable supplies of ground water to a much smaller degree. Clay, shale, anhydrite, and most igneous rocks, retard the movement of water, and in the places where these rocks are dominant, large supplies of water of satisfactory quality are difficult or impossible to obtain.

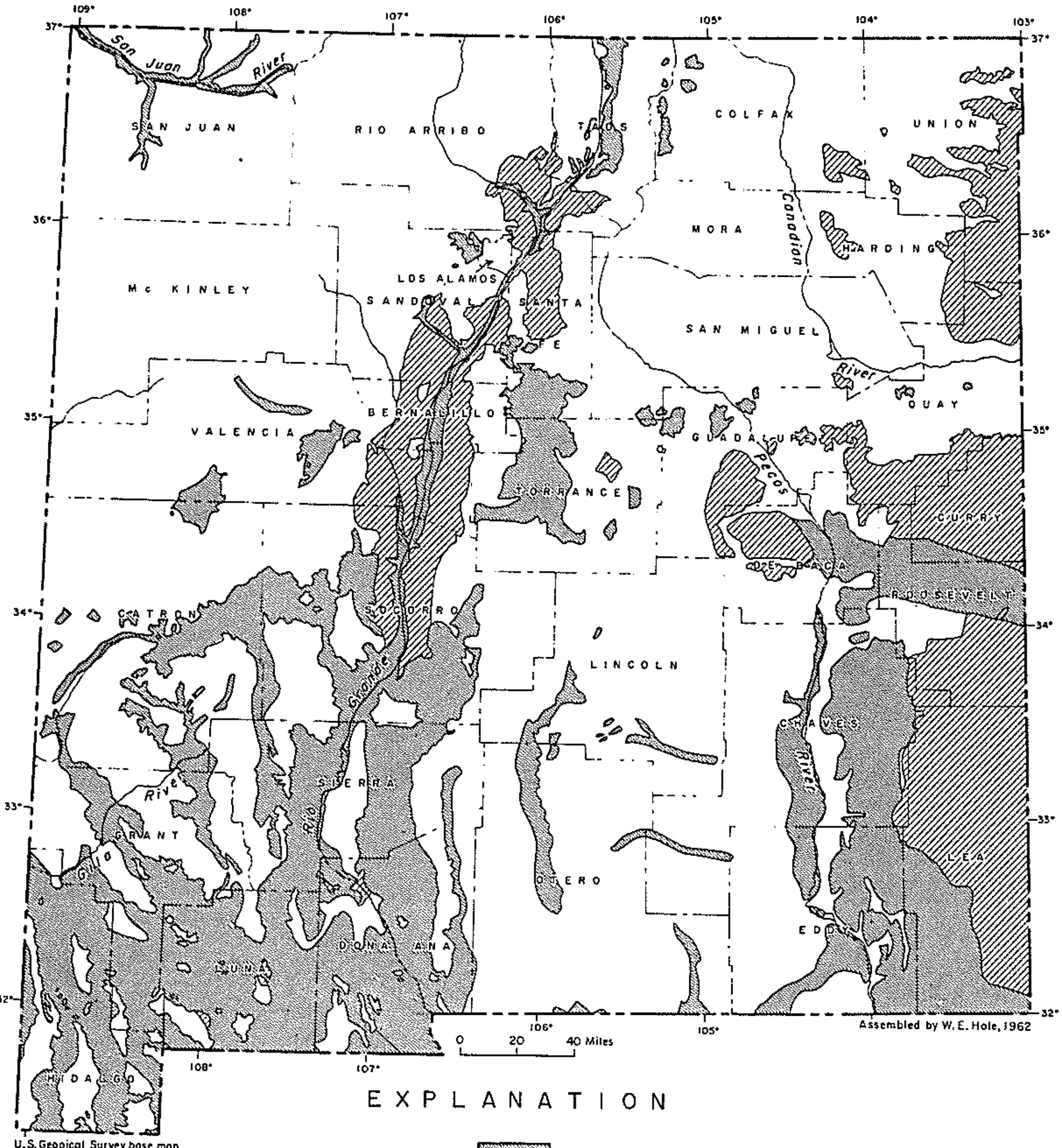
SAND AND GRAVEL AQUIFERS

The areal distribution of the principal sand and gravel aquifers in the State is shown in figure 1. Some consolidated sandstone and conglomerate deposits of Tertiary age are included in the areas shown on figure 1 because these rocks are closely associated hydraulically with the adjacent or overlying deposits of unconsolidated or poorly consolidated sand and gravel.

The sand and gravel underlying the High Plains are the western part of an extensive group of aquifers in Texas and Oklahoma and states farther north. In several places in Lea and Curry counties, wells yield more than 1,000 gpm (gallons per minute) from this aquifer. Yields of more than 300 gpm are common. Depths to water range from about 30 feet to more than 180 feet in northern Lea County. In parts of Curry County, the depth to water is more than 350 feet. In most of the other parts of the High Plains, the depth to water is about 100 feet.

Considerable difficulty with sand entering wells occurs in Lea County and other places on the High Plains. This difficulty might be avoided in some places by leaving the wells open only to beds of gravel in buried stream valleys at the base of the sand and gravel aquifers.

The quality of water is generally good. However, the fluoride content of the water in many places is higher than that recommended for domestic use by the U.S. Public Health Service.



EXPLANATION

Aquifers in sand and gravel of Quaternary and Tertiary age

Aquifers in sand and gravel of Tertiary age

Figure I.--Distribution of principal sand and gravel aquifers in New Mexico

In Portales Valley in northern Roosevelt County, the alluvium has yielded 300 to 1,000 gpm to wells. Initial depths to water were about 15 to 30 feet. The quality of water is good, but the water has become somewhat more highly mineralized as a result of recharge from irrigation return water.

The alluvium is commonly thin west of the High Plains, south of De Baca County, and east of the Pecos River. Large supplies of water generally are not available in this area. In southern Lea County, however, ground water in a thick local alluvial deposit probably will supply the town of Jal for the foreseeable future. This thick alluvial deposit probably is the northern extension of a much thicker alluvial trough that extends south into Texas.

Another deep alluvial filled trough extends into New Mexico from Texas a few miles west of the trough that supplies water for Jal. In Texas these troughs are as much as 1,500 feet deep. The fill has been deposited in a trough probably created by a solution of salt that underlies much of this region. Water of good quality exists in the upper part of the fill.

The sand and gravel aquifer in the Pecos Valley extending south from the vicinity of Roswell in central Chaves County to Lake McMillan in central Eddy County and south of Carlsbad to Black River in south-central Eddy County has been utilized extensively for irrigation supplies for many years. Yields of more than 1,000 gpm are common. The high yields generally are obtained from fractures and solution zones in the conglomerates in the valley fill. In both the Roswell basin and Carlsbad basin the alluvium is thicker than might ordinarily be expected because the original basin was deepened by solution of the underlying gypsum and limestone.

Thick alluvium and bolson deposits exist in southeastern Otero County and along the Tularosa Basin in western Otero County and southwestern Lincoln County. However, the zone of saturation is below the alluvium in southeastern Otero County, and the aquifer in the central part of the Tularosa Basin contains water too saline for use without extensive treatment. Considerable fresh water does exist in the alluvium along the slopes off the bordering mountains. Water has been developed for irrigation use and municipal use along the eastern margin of the Tularosa Basin in the vicinity of Carrizozo in Lincoln County southward to Alamogordo in Otero County. Along the western margin of the Tularosa Basin, water has been developed from the alluvium to supply the White Sands Missile Range. Large volumes of fresh water underlie the western margin of the Tularosa Basin south of White Sands in southeastern Dona Ana County. This source of ground water is not developed at this time but is available to future developments in the Tularosa Valley.

The alluvium in Estancia Valley in Torrance and Santa Fe counties yields 200 to 1,200 gpm to wells bordering Highway 41, which runs north through the central part of Torrance County. Farther east, the water in places is too saline for irrigation use. To the west, the alluvium is much thinner, and depths to water are about 150 feet. Here the yield from wells is small.

In the southern Jornada del Muerto in north-central Dona Ana County, large supplies of potable water probably could be developed although this area is largely untested. Farther north, the water at most places is not potable, but locally it may be suitable for irrigation use.

The valley of the Rio Grande is remarkable because of its length, its width, and the depth of its alluvium. The Rio Grande throughout its course in New Mexico flows in a system of connected downthrown blocks. Various blocks have been displaced downward thousands of feet, and the trench has been filled mostly with alluvium. The depth of this fill is not known at many places, but in the vicinity of Albuquerque it is at least 6,000 feet. The total displacement of rocks along some of the faults is on the order of 20,000 feet or about 4 miles from the crest of the mountain to the top of the equivalent rocks in the trough. The Rio Grande trough is 15 to 30 miles wide from the vicinity of Socorro in central Socorro County northward to the Colorado State line and is much narrower in places south of Socorro to the Texas State line. Thus, there appears to be a vast volume of water in the alluvium of the Rio Grande Valley, and much of the contained water is of good quality. In places, tributary valleys, such as those of the Rio Puerco and Rio Salado in Socorro County, contribute moderately saline water.

Large yields of water are obtained from the alluvium, and the depth to water is only a few feet below land surface along the narrow central flood plain of the Rio Grande. Away from the flood plain, the depth to water increases as the land rises toward the flanking mountains.

The lowest part of the water table from the vicinity of Belen in Valencia County northward to the vicinity of Los Alamos is not along the river, as might generally be expected, but is several miles west of the river. In places along this depression, the water table is as much as 40 feet below the river level to the east. Such a depression in the water table may be the result of lack of recharge on the west side of the valley, but more probably the sands and gravels here may be more permeable and much thicker than in the vicinity of the river. The water table in places is more than 1,000 feet deep along the west margin of the Rio Grande trough in this locality.

In the Rio Grande and most other river valleys, the water in the alluvium is interrelated hydraulically to the water in the surface streams. Intensive development of ground water therefore diminishes ground-water additions to the streamflow of the river, and in time the river may lose water to the ground-water reservoir, as rivers do in many parts of the Southwest. In areas such as the Rio Grande where surface waters are fully appropriated, uncontrolled development of the adjacent ground-water reservoir would create problems although the valley contains large volumes of ground water that extend to great depths. Development of even small amounts of ground water near the Rio Grande will quickly affect the river regimen.

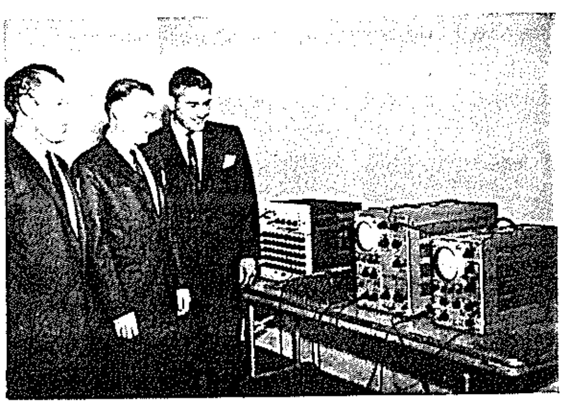
In the Basin and Range province in the southwest part of the State and west of the Rio Grande, the intermontane valleys are partly filled with extensive deposits of sand and gravel and older sandstone and conglomerate. One of the oldest irrigation developments in the State, the Deming area in Luna County, obtains water from alluvium. Here the depth to water is commonly less than 100 feet. Other irrigated areas include the Animas and Playas Valleys in Hidalgo County and, more recently, the valleys around Lordsburg in Hidalgo County and southern Grant County. In general, water is obtained from the upper part of a sand and gravel section. In this region, water also occurs within permeable beds and fractures in hard conglomerate at depths that discouraged drilling to some extent. Moderate to large water supplies probably could be developed from sands and gravels that are interbedded with basalt flows in the upland areas, but the depth to water commonly is great.

Farther north, in the valley of the Rio San Jose in Valencia County, water has been developed for irrigation and industrial use near Grants in north-central Valencia County. Downstream, water can be developed in places for irrigation use on the Acoma-Laguna Indian Reservations. However, in much of the lower valley of the Rio San Jose, the water may be too highly mineralized for even irrigation use.

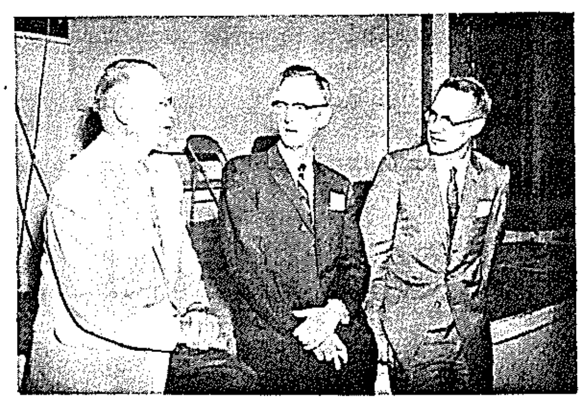
The alluvium in the San Juan Valley in San Juan County locally yields potable water, but here the alluvium is thin and spotty and in many places contains saline water. Towns along the San Juan River utilize surface water for municipal supplies.

New Mexico State University President Roger B. Corbett, left, with Mr. O. M. Hackett, Chief of the Ground Water Branch, U. S. Geological Survey, Washington, D. C.; Dean Frank Bromilow, College of Engineering, N.M.S.U.; and Dr. H. Ralph Stucky, Water Conference Chairman and Head of the Department of Agricultural Economics and Agricultural Business, N.M.S.U. President Corbett delivered the Address of Welcome and Mr. Hackett was the keynote speaker of the Conference.

This group, Dean Frank Bromilow, N.M.S.U.; Professor Nathaniel Wollman, University of New Mexico; State Engineer Steve Reynolds; and Jack Lacy, Deputy Director, Department of Development, relax a bit just prior to the start of a Conference session.



Wm. P. Stephens, Agricultural Economist, N.M.S.U.; Ralph Charles, Engineer, Bureau of Reclamation, Albuquerque; and F. X. Bushman, Ground Water Geologist, New Mexico Institute of Mining and Technology, Socorro, looking over the electronic equipment used by ground water geologists in studying ground water supplies.



Left to Right: William E. Hale, Engineer, Ground Water Branch, U.S. Geological Survey; Joe Yates, Chief, Technical Division, State Engineers Office; and Dr. James R. Gray, Agricultural Economist, N.M.S.U. considering water resources problems in New Mexico

LIMESTONE AQUIFERS

The second most important group of aquifers in New Mexico are in limestone. Figure 2 shows the principal areas in which these aquifers have been developed or contain water of fair quality. These areas are in the Pecos Valley, southeastern Otero County, some of the mountain areas as in the Sandias and Manzanos, the area in the general vicinity of Grants, and a few small places in the southwestern part of the State.

Limestone formations of Pennsylvanian age contain water in the upper Pecos River drainage. These limestone formations commonly contain much clayey material, which has retarded the development of solution channels, and the limestone itself has a low permeability. Small supplies of water generally are obtained from fractures. Adequate supplies for domestic use should be obtained from this limestone aquifer in the mountains, but the depth to water or the depth of wells required to develop these supplies are not known at this time. Farther south in the vicinity of Santa Rosa in Guadalupe County, large supplies of water can be developed from the San Andres Limestone of Permian age from wells drilled to below the elevation of the Pecos River. A large part of the recharge to this aquifer is from the river to the north. As the water moves southward through the aquifer, it dissolves large amounts of sulfate from the gypsum within and adjacent to the aquifer. The aquifer discharges large amounts of high sulfate water along the Pecos River Valley from Santa Rosa southward to Puerto de Luna in southern Guadalupe County. The water is suitable for irrigation use.

The limestone aquifer in the San Andres in the vicinity of Santa Rosa is probably continuous with the aquifer farther south in the vicinity of Roswell in Chaves County. It is not shown on the map, because in parts of this area the aquifer contains saline water, and in other parts data are lacking.

In this region, several tens of miles north of Roswell, water in the San Andres possibly may move east of the river and thence into the southeast corner of the State. This water probably is highly saline. Perhaps the recharge for this part of the system could be prevented from entering the aquifer by diverting it more directly to the Pecos River. The water might be better utilized by holding the water on the land for more intensive growths of grass, for it seems that little recharge of ground water takes place unless the water if ponded or enters stream channels.

The San Andres Limestone and the younger Grayburg Formation form the famous artesian aquifer of the Roswell basin mostly in Chaves and Eddy counties. In the western part of the Roswell basin, the water is unconfined, and water is 300 to more than

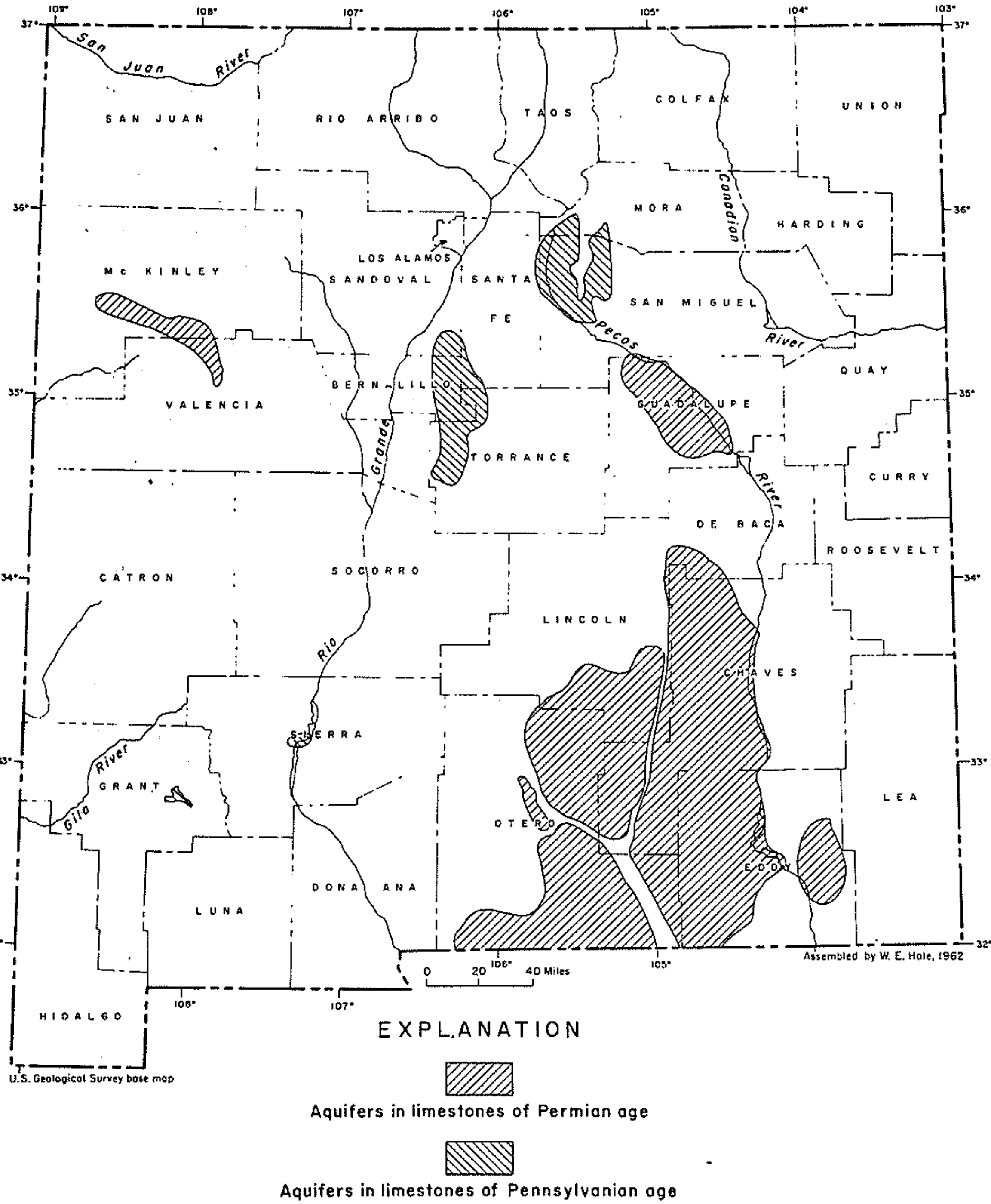


Figure 2.-- Distribution of principal limestone aquifers in New Mexico

1,000 feet deep in places. Farther east, as the aquifer dips to the east, it is overlain by partially confining beds. In the early 1900's, more than a thousand flowing wells were constructed in the artesian aquifer. The artesian pressure has declined over the years, and many of the artesian wells have been equipped with pumps. The area of flowing wells is now in a narrow band along the river and some of the larger tributaries. Wells range from a few hundred feet in depth in the northern part of the area of flowing wells to more than 1,000 feet in the southern part and yields of a few thousand gallons per minute are common.

The limestone aquifer continues eastward from the Pecos River, and some of the fresh water may possibly move east. One such area may exist east of Artesia in northern Eddy County, where relatively fresh water is developed from a well into the limestone a few miles east of the river. However, most of the fresh water in the system is discharged from the aquifer into the alluvium, either directly or through the semiconfining bed, and thence to the Pecos River.

Water is available in the limestone of the Yeso Formation of Early Permian age in the Sacramento Mountains in Lincoln, Otero, and Chaves counties. Ground water, in quantities sufficient for irrigation use, is in these rocks at shallow depths along the principal drainageways. In the highlands, recharge takes place through the San Andres Limestone cap and moves downward and eastward through the limestone beds of the Yeso Formation. Depth to water in many of the stock wells is more than 500 feet. A part of the water moving eastward through this system of rocks discharges into the San Andres Limestone and may amount to a substantial part of the recharge to the artesian system of the Roswell basin. The zone along which the water moves from the Yeso Formation and an immediately overlying sandstone aquifer into the San Andres Limestone is defined remarkably well by the change in slope of the water table or pressure gradient. To the east, in the San Andres, the gradient of the water table is a few feet to the mile; to the west, in the Yeso, the gradient is 75 to 100 feet to the mile.

The aquifers in the Carlsbad area, mostly in western Eddy County, are in limestone units that are younger than the San Andres and separate from the system of the Roswell basin. These rocks dip gently a little north of east. In the highlands of Guadalupe Mountains in Chaves, Otero, and Eddy counties; there is a series of limestone units stacked one upon another and separated by semipermeable silty sandstone beds. The water moves in these units to the east and north to merge into a common aquifer along the east front of the Guadalupe Mountains. This common aquifer is a permeable limestone reef which in this area serves as a large collecting gallery for the less permeable limestone aquifers in the high country of the Guadalupe Mountains. This aquifer discharges much of its water to the Pecos River at Carlsbad Springs in central Eddy County.

Large supplies can be obtained from the reef limestone. It is probably as permeable as the more permeable parts of the artesian limestone aquifer of the Roswell Basin. Within the reef aquifer, water levels are only slightly higher than the level of Carlsbad Springs several miles to the southeast. Because of recharge of slightly saline water to the limestone system north of Carlsbad, the water is highly mineralized in parts of Carlsbad. Farther to the southwest the water is of good quality, and the city has recently extended its well field to that locality to obtain the better water. Small supplies of water of fair quality can be obtained in perched aquifers in the less permeable limestones to the west of Carlsbad.

The reef limestone aquifer extends into the subsurface east from Carlsbad and swings southward into Texas along the Lea-Eddy County line. At Hobbs, water pumped along with the oil from some wells has a very low dissolved-solids content. Perhaps some of the fresh water in the Carlsbad area moves eastward from Carlsbad through the reef aquifer to discharge finally into the Pecos River several tens of miles southeast of Carlsbad where there is a large increase in the flow of the river. It would be interesting to test drill the reef aquifer in this area to learn whether this is so and how much water is moving through the system.

Water is obtained also from a limestone unit in the Rustler Formation of Permian age east and south of Carlsbad. In much of the area, the water is saline, but locally the quality is good enough for stock use.

In southeastern Otero County, limestone of the Yeso Formation, Hueco, and Bone Spring Limestones are permeable and yield large supplies to wells. The limestone in these formations is the northern part of the limestone aquifer developed intensively in the Dell City area in Texas. However, the land surface rises to the north and east in New Mexico, and since the water table is nearly flat, the depth to water is great, reaching 800 feet about 20 miles north and west of Dell City. Here the water is only of fair quality but is suitable for irrigation use.

In the Sandia and Manzano Mountains in Bernalillo, Sandoval, Santa Fe, and Torrance counties, limestone of Pennsylvanian age, similar to that in the headwaters of the Pecos, yields small supplies to wells. Water from these rocks generally is available in sufficient quantity and is of adequate quality for domestic use to supply the large number of summer homes being built in the area.

Important supplies of hot water are obtained from an artesian aquifer in limestone at Truth or Consequences in central Sierra County. Farther southwest, small supplies of water are obtained from the limestone for use in the mining industry near

Santa Rita in east-central Grant County.

Water of good quality from the limestone aquifer in the San Andres in the vicinity of Grants in Valencia and McKinley counties is obtained from wells only a few hundred feet deep. The water is suitable for industrial, irrigation, and municipal uses. Northwest from Grants, at some distance from the Zuni Mountains in Valencia and McKinley counties, wells tap water in the San Andres at a depth of more than 1,000 feet, but in places along the flank of the Zuni Mountains, flowing wells of small to moderate yield have been constructed in the San Andres Limestone.

The San Andres generally contains saline water to the north and south of the Zuni Mountains. To the east it may contain water of useable quality, and in this area where water is good quality is scarce in shallower formations, test drilling in the San Andres, to learn more of the quality of the water and yield of the aquifer seems warranted.

SANDSTONE AQUIFERS

The principal sandstone aquifers in New Mexico are in the northern part of the State (figure 3). The yield of sandstone aquifers tends to be more uniform than that of the sand and gravel or limestone aquifers. The permeability of the sandstone aquifers is quite low in general, but in places, where the sequence of sandstone beds is thick, moderate to large yields of water can be obtained. The sandstone aquifers are composed of a number of sandstone units ranging in age from Pennsylvanian to Tertiary.

The Sangre de Cristo Formation of Pennsylvanian and Permian age, on the eastern and southern flanks of the Sangre de Cristo Mountains in the northeastern part of the State, probably will yield small supplies of water of good quality. The Glorieta Sandstone of Permian age yields small to moderate supplies of water to wells in San Miguel, Torrance, and Lincoln counties.

The younger Santa Rosa Sandstone of Late Triassic age yields small supplies of water in southeastern Santa Fe County. The Santa Rosa also yields small to moderate supplies of water to wells in Guadalupe County and east of the Pecos River in Chaves, Eddy, and Lea counties. Sandstone beds in the Chinle Formation of Late Triassic age in parts of Guadalupe and Quay counties yield only a few gallons per minute to wells, but in many of these places it is the only water of suitable quality for domestic and stock use. The sandstones of the Chinle yield small supplies of water in Roosevelt, Chaves, and Lea counties.

The Entrada Sandstone of Jurassic age is an important aquifer near Tucumcari in Quay County. Moderate supplies of water of good quality have been developed in this sandstone for municipal use by the city of Tucumcari.

Farther north, the Dakota Sandstone of Early(?) and Late Cretaceous age yields water of useable quality in places. In the still higher country, beneath basalt, the Raton (Cretaceous and Paleocene) and Poison Canyon (Paleocene) Formations may be expected to yield water to wells.

The sandstone aquifers in northwestern New Mexico are varied in character. Some contain a large ratio of clay and silt to sand; some consist of well-sorted sand grains, and the sand grains vary in size from very fine to coarse. Most of the sandstone is firmly cemented, although some units are loosely cemented and friable.

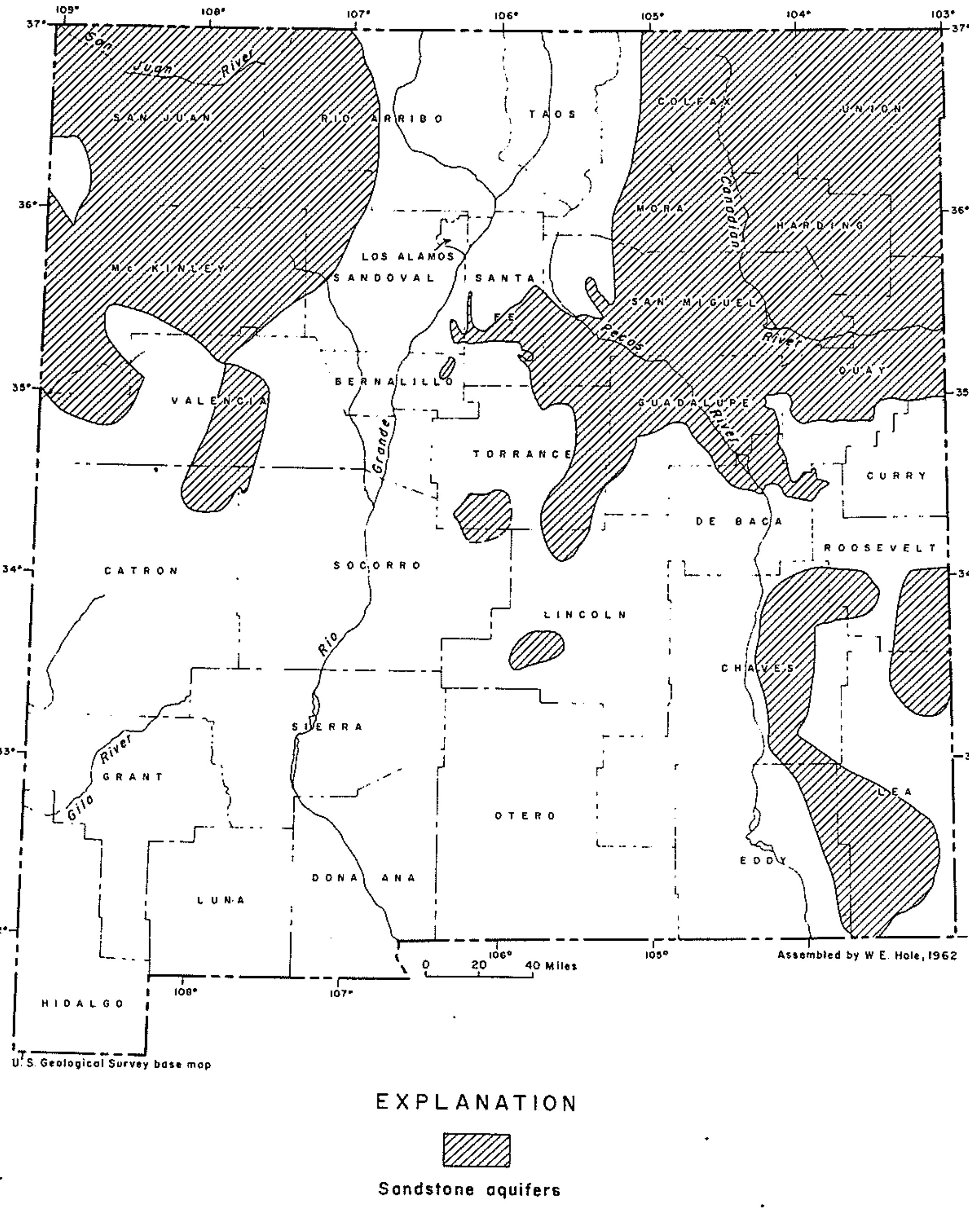
The Gallup Sandstone (Late Cretaceous) yields as much as 250 gallons per minute of potable water to wells at Gallup in western McKinley County, and yields of 10 to 75 gpm for the Gallup Sandstone are common where it occurs in the subsurface throughout southern McKinley County. The Ojo Alamo Sandstone (Late Cretaceous) yields as much as 30 gpm of potable water to wells in eastern San Juan, western Rio Arriba, and northern Sandoval counties. The San Jose Formation (Eocene) yields as much as 60 gpm of potable water to wells in western Rio Arriba County, but the ground-water potential of the formation has not been tested.

Electric logs of wells that have been drilled for oil and gas indicate that the cumulative thickness of water-bearing sandstone in the Ojo Alamo Sandstone, Nacimiento (Paleocene), and San Jose Formations, in western Rio Arriba County is as much as 1,800 feet. Based on the yields of wells that tap only a few feet of sandstone, a properly constructed well that tapped all these beds of sandstone possibly would yield as much as 3,500 gpm of water. This area probably has the greatest potential for ground-water production of any area in northwestern New Mexico, exclusive of the Grants-Bluewater area.

Yields of other sandstone aquifers in northwestern New Mexico generally are less than 10 gpm. Domestic-and stock-water supplies generally can be obtained from sandstone aquifers in the northwestern part of the State, although potable-water supplies are scarce in some large areas.

DEPTH TO WATER

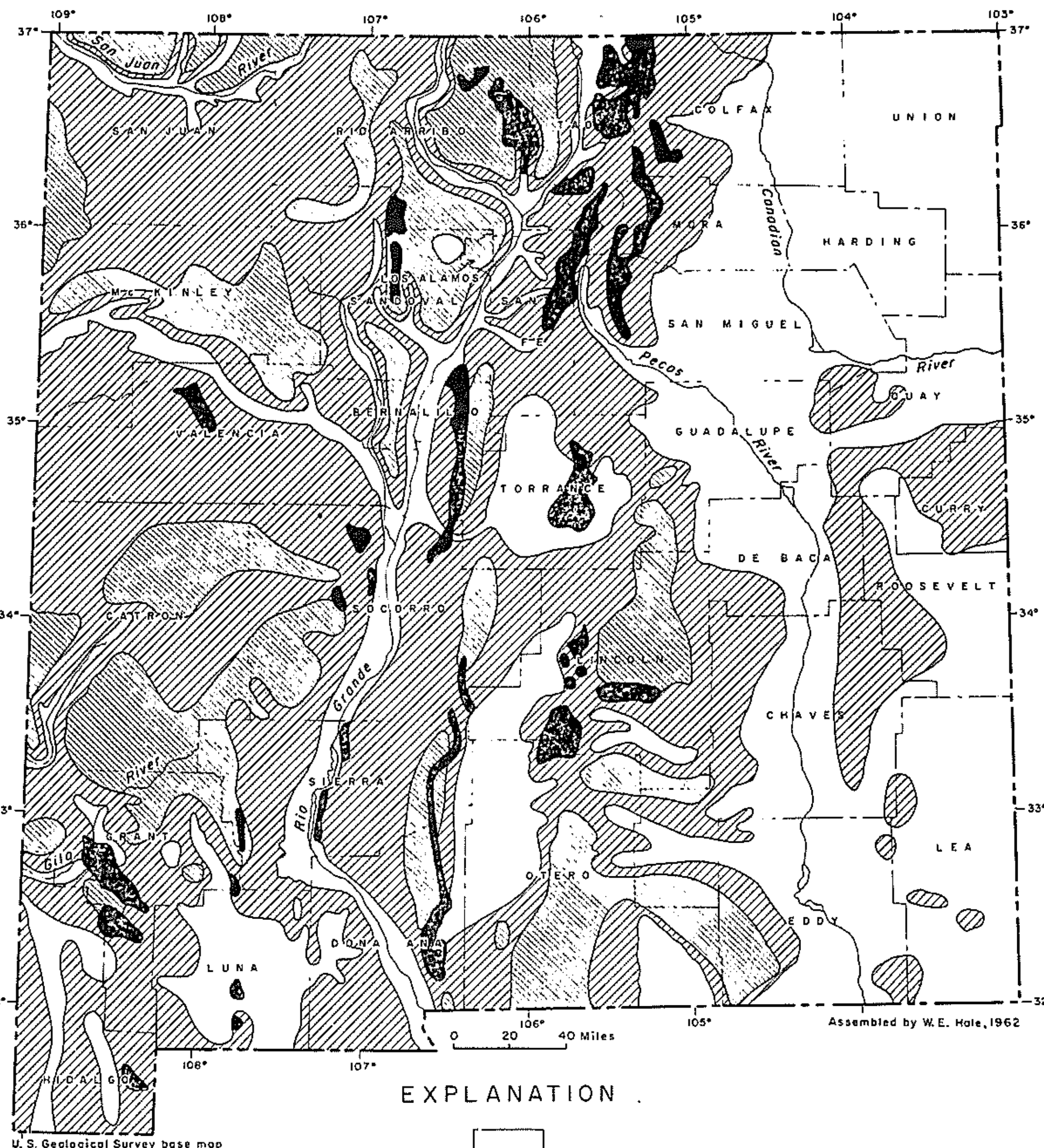
Depth to water is an important economic aspect of ground-water supply. Figure 4 shows the depth to water in variable intervals: less than 200 feet, 200 to 500 feet, and more than



EXPLANATION

Sandstone aquifers

Figure 3.--Distribution of principal sandstone aquifers in New Mexico



EXPLANATION

Less than 200 feet

200 to 500 feet

More than 500 feet

Areas underlain by Precambrian and igneous rocks, assumed to be not water bearing

Figure 4. -- Depth to ground water in New Mexico

500 feet. In most of the valleys and plains areas, the depth to water is less than 200 feet, and it is in this depth range that water for irrigation use has been most intensively developed. In a few places such as Curry County and parts of the Pecos Valley, where lifts of more than 200 feet are required, water has been utilized for irrigation in spite of the greater than ordinary lift, but in Curry County, where rainfall some years may be almost sufficient to produce a crop, it has apparently been economical to pump a short time at these greater lifts to get the crop over the hump. Pumping from great depths is not so critical a factor for supplies developed for municipal and industrial use.

In several areas in the State, the depth to the water-table is more than 500, and in places more than 1,000 feet. One such area is in northwestern Eddy County. Other areas of great lift are in the high country in northern Grant and southern Catron County and along the west margin of the Rio Grande Valley north of Albuquerque to Los Alamos. In one small area along the south flank of the Jemez Mountains in Sandoval County, the depth to water probably is more than 1,500 feet.

In many areas where the depth to water is more than 500 feet, wells have been abandoned as dry before they reached the water table, because no one believed water could be so deep. Areas where Precambrian or intrusive rocks, which are nearly non-water-bearing, are also shown on figure 4.

The areas in which small, moderate, and large yields of ground water can be obtained are shown in a general way on figure 5. These areas more or less coincide with the areas of the sand and gravel and limestone aquifers (figures 1 and 2). In many of the areas of high yields, supplies of more than 1,000 gallons per minute are common.

QUALITY OF WATER

The areas in New Mexico where supplies of potable water are scarce are outlined on Figure 6. Actually the figure shows the areas in which ground water commonly contains more than 1,000 parts per million dissoved solids. These areas cover a large part of the Pecos Valley, the Tularosa Basin, the limestone upland in southeastern Otero County, much of the Jornada del Muerto, and northwestern New Mexico.

The water is only slightly saline in many parts of the areas where potable water is scarce, and it might be economically feasible to salvage some of this water by utilizing various saline-water-treatment methods. The saline-water-treatment plant to be built at Roswell should provide information on operational and economic factors.

SUMMARY

The most imporatnt sand and gravel aquifers are in the southeastern and southwestern part of the State and in the Rio Grande Valley. Limestone aquifers predominate in the south-central part of the State and in the Grants area. Sandstone aquifers occur primarily in the northeastern and northwestern part of the State.

The depth to water in much of the area at the lower elevations in the State is less than 200 feet. Locally, at the higher elevations underlain by limestone and sand and gravel, the depth to water is more than 1,000 feet.

Supplies of water containing less than 1,000 parts per million of dissolved solids are scarce in a large part of the Tularosa Basin, the Pecos Valley, and parts of northeastern and northwestern New Mexico.

Much work remains to be done to define our total water supply. Adequate qualitative areal studies have yet to be made in a large part of west-central and northeastern New Mexico. Furthermore, investigations should be extended to those aquifers containing moderately saline water inasmuch as these waters may be economical to treat and utilize in the not too distant future. Qualitative studies should extend to aquifers containing highly saline water and to poorly permeable aquifers to define areas in which wastes of all kinds can be stored with the least contamination hazard.

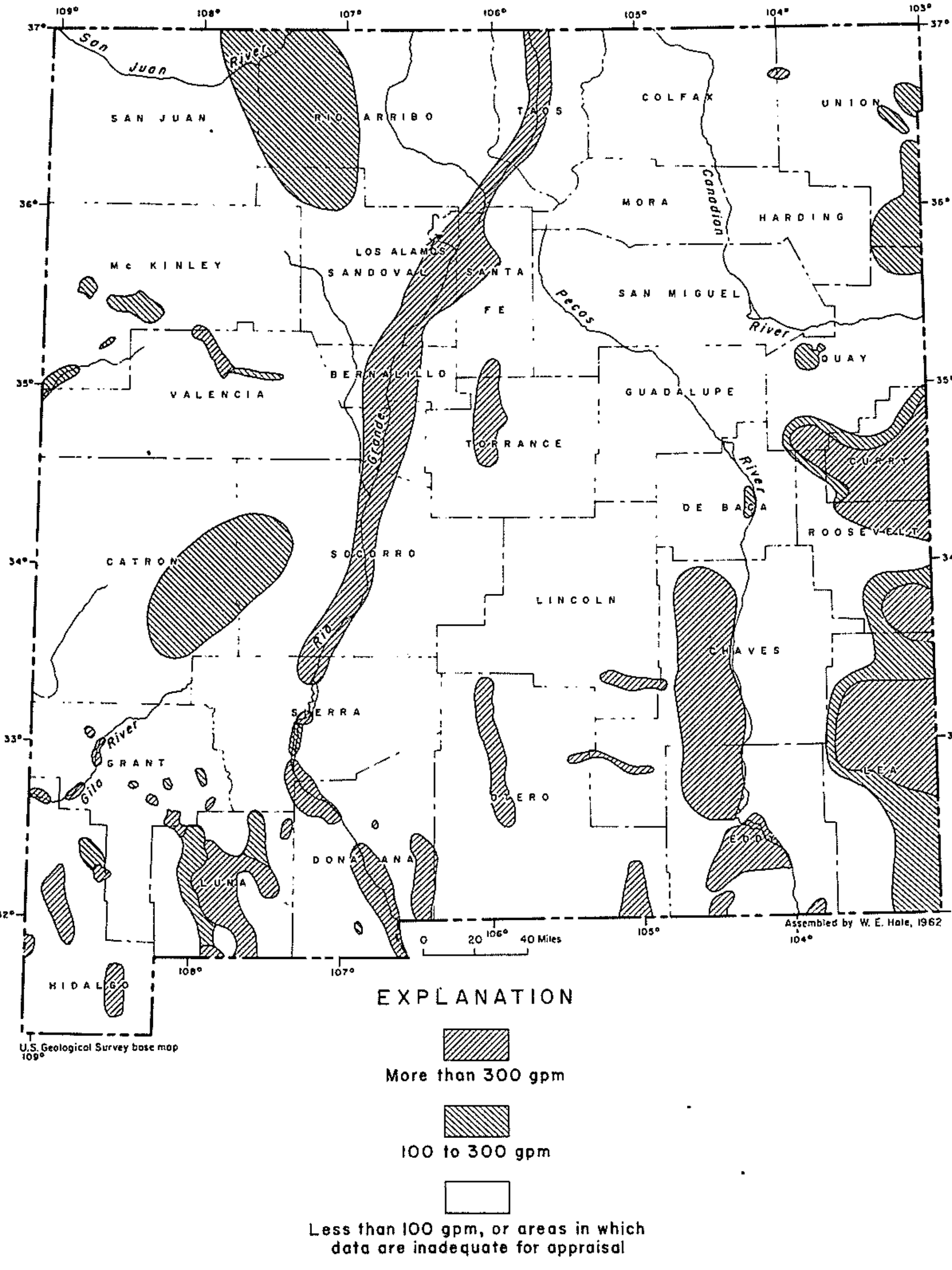
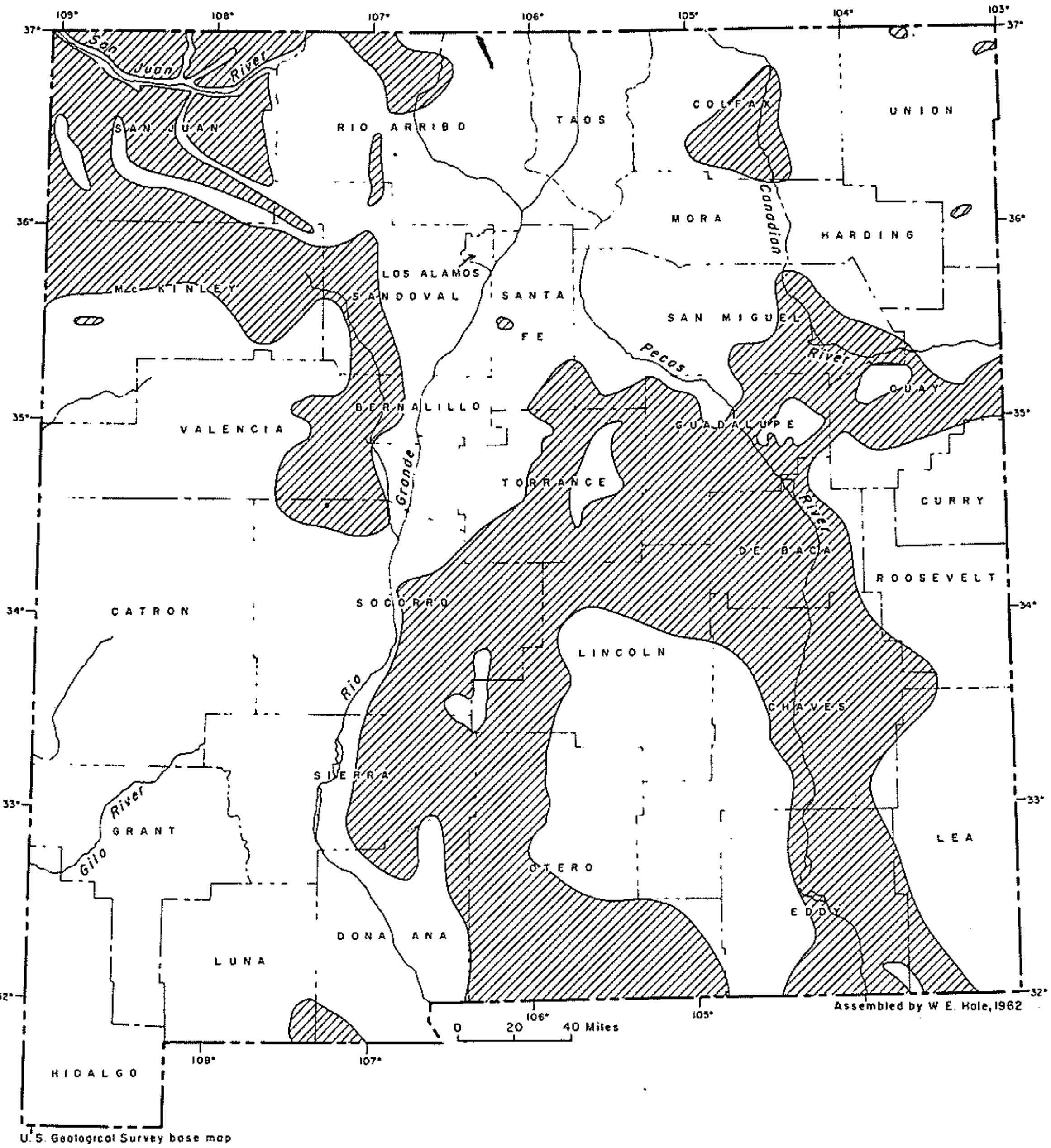


Figure 5.--General availability of relatively fresh ground water in New Mexico



EXPLANATION

Areas in which ground water commonly contains more than 1,000 ppm of dissolved solids

Figure 6.--Areas in New Mexico where supplies of relatively fresh ground water are scarce

CHANGES IN QUANTITY OF GROUND WATER

J. C. Yates[1/]

The importance of ground water in New Mexico is indicated by its uses. It supplies more than 90 percent of municipal and industrial requirements. It is the only source of water to irrigate about one-half the State's total irrigated area and it furnishes supplemental water to almost one-third of the area irrigated from surface-water supplies. The development of the resource has largely occurred during the past two decades. Ground-water use has increased the State's irrigated area by about 325,000 acres since 1940, and diversion for municipal and industrial use has increased at rates greater than population expansion.

Ground water is contained in subsurface reservoirs which provide a medium for storage and transmission of water from areas of intake to areas of discharge at the land surface. Under natural conditions, reservoirs are in a state of approximate equilibrium. When wells into the reservoir pump or flow, a new or artificial discharge is superimposed on the hydraulic system. The water so diverted must derive from increased recharge, decreased discharge, from storage, or from a combination of these sources. Initially a pumping or flowing well takes water from storage. The effect of pumping, whether pumping is continued or not, spreads radially outward from the well and in time reaches areas of recharge and areas of discharge. If, in the areas of recharge, the reservoir had perviously rejected water, the effect of pumping may cause the reservoir thereafter to take more water. Pumping effects reaching areas of discharge will cause diminution of discharge. The total effect on a reservoir by artificial diversion from wells is the sum of the effects of individual wells.

I will briefly describe some representative reservoirs from which irrigation developments have been made and the changes that have been observed.

HIGH PLAINS

In eastern New Mexico large irrigation developments have been made from ground-water reservoirs located on the southern High Plains. These reservoirs which immediately underlie the surface consist of loose or poorly consolidated fine sand and various mixtures of clay, sand, and gravel. The western limit of the plateau upon which these reservoirs are located is defined in most places by an escarpment exposing sections of the reservoir rock. Bedrock is a sequence of consolidated sedimentary rocks in which water deposits of economic importance have not been proven.

1/ Chief, Technical Division, New Mexico State Engineer Office, Santa Fe, New Mexico.

The ground-water reservoirs are recharged by precipitation, mainly from runoff in the drainage ways and in the numerous depressions that dot the plain. Natural discharge from these reservoirs is by seeps and springs at the eastern boundary of the High Plains in Texas. Idealized, the aquifers are wedge-shaped, the thickness of saturated sediments increasing as recharge from precipitation accumulates eastward in the direction of ground-water flow.

Principal High Plains areas of irrigation in New Mexico are located near House in Quay County, in the Clovis area, in Portales Valley, and in the Causey-Lingo and Tatum-Lovington-Hobbs areas.

House area, Quay County

In the House area in southwestern Quay County, the Ogallala formation provides an aquifer in which saturated sediments range in thickness from 25 to 100 feet and average about 50 feet. Depths to water range from 25 to 100 feet. Water levels fluctuate in response to pumping and only in years of heavy precipitation is recharge significant.

Irrigation began in 1936 when four wells pumped about 380 acre-feet of water. The amount of irrigated land increased progressively until 1950 when about 4,400 acres was irrigated. Since 1950 irrigation has decreased and averaged about 3,500 acres from 1950 to 1960.

In the 19 years from 1941 to 1960 about 85,000 acre-feet of water was pumped for irrigation. In the 9 years from 1941 to 1950 water levels declined in excess of 5 feet under an area of 1/4 square mile. During the next 10 years the area of 5-foot decline had spread to 25 square miles and within that area the maximum decline was in excess of 20 feet.

Clovis area, Curry County

The Ogallala formation mantles the Clovis area in Curry County and is the principal aquifer in a saturated zone ranging from about 45 feet in the vicinity of Melrose to about 200 feet in the southeastern part of Curry County. Depths to water range from 130 to more than 330 feet. It is estimated that the water in storage in the Clovis area in New Mexico aggregates about 5 million acre-feet. Annual recharge is about 15,000 acre-feet.

The Ogallala formation of the Clovis area grades into the reworked material that comprises the Portales Valley aquifer. The two reservoirs are contiguous and hydraulically connected. Their common boundary is defined by a water-table ridge located north of Blackwater Draw. The location of that boundary may be changed by the effects of pumping in both reservoirs.

In the Clovis area the first successful irrigation wells were drilled about 1948 and rapid development of irrigation began in

1953. By late summer in 1955 more than 400 wells had been drilled and about 74,000 acres were irrigated. Since 1956 the area irrigated has averaged about 80,000 acres and the pumpage has amounted to about 80,000 acre-feet per year.

Interpretations of water-level changes from 1954 to 1960 indicate that declines may have exceeded 20 feet in an area of 33 square miles. A more significant decline of 5 feet is observed under 310 square miles.

Portales Valley, Roosevelt County

Portales Valley is a broad and shallow depression on the High Plains. Water flows in the few stream courses only after infrequent heavy rainfall and accumulates in playas and depressions.

The ground water reservoir is composed of reworked and redeposited materials from the Ogallala formation. Recharge is from infiltration of precipitation, a favorable area being a belt of sand dunes that extend along the north side of the valley. Ground water moves east-southeast along the axis of the valley, and is discharged naturally by evaporation from water-table lakes, evaporation from areas where the water table is near the surface, flow from a few small springs, and subsurface flow acrpss the State line. Pumpage from wells has imposed an artifical discharge on the reservoir, causing substantial depletion to the reservoir.

Irrigation in the Portales Valley began in 1910 when the Portales Irrigation Company was established. About 4,000 acre-feet of water was pumped annually until 1914 when the company failed. By 1929, the irrigated area had increased to about 4,800 acres. Irrigation of 56,000 acres in 1960 is an 8-fold increase over the estimated 7,400 acres irrigated in 1932.

Water pumped for irrigation in the 18-year period from 1932 to 1950 totaled about 470,000 acre-feet, and water levels declined more than 5 feet under 60 square miles, and more than 10 feet under 34 square miles. Pumpage for irrigation during the 10-year period from 1950 to 1960 was about 870,000 acre-feet, and water levels declined from the 1949 datum more than 10 feet under 150 square miles, more than 20 feet under 65 square miles, and more than 30 feet under 12 square miles. Along the axis of the valley in the center of the irrigated area, net declines averaged about 1/2 foot per year from 1932 to 1950, and about 2-1/2 feet per year from 1950 to 1960.

Lea County

In New Mexico the largest ground-water reservoir on the High Plains is in the Ogallala formation covering about 2,000 square miles of Lea County. Large irrigation developments have been made in the Tatum-Lovington-Hobbs area where irrigation has increased from less than 1,000 acres in 1930 to about 95,000 acres in 1960. The thickness of the saturated sediments ranges from zero to more than 200 feet and averages about 95 feet. Wells yield moderate to large quantities of water of good chemical quality. In the area of extensive irrigation development, pumping lifts range from 55 to 115 feet and average about 85 feet.

Average annual recharge to the reservoir in New Mexico is about 29,000 acre-feet and the amount of water in storage in New Mexico approximates 27 million acre-feet. The reservoir extends beyond the State line into Texas, where large irrigation developments are continuing to be made.

In the Tatum-Lovington-Hobbs area about 146,000 acre-feet of water was pumped for irrigation from 1940 to 1950. In the next decade, 1950-1960, pumpage for irrigation was 10 times greater or about 1,470,000 acre-feet. Water-level measurements from 1940 to 1950 did not reflect significant declines. However, because of the large annual amounts of water pumped beginning about 1948, data recorded from 1950 to 1960 indicated declines of more than 5 feet under 550 square miles, more than 10 feet under 310 square miles, and more than 20 feet under 35 square miles.

In Lea County essentially all pumping is from storage--that is, the water is being mined. Presently only an insignificant amount of annual recharge is pumped. As the reservoir is depleted, flows to Texas will decrease and increasing amounts of recharge will be intercepted by wells. Only when the water in storage has been depleted will pumping be limited to the recharge.

CLOSED DRAINAGE BASINS

In New Mexico important developments for irrigation have been made in basins which are closed topographically and in which surface drainage is to playa lakes. Usually the valley floors of these basins are relatively flat, and normal flows in streams on the slopes of bounding mountains do not reach the playas. The rocks underlying the valley floors are generally derived from adjacent mountain masses and vary markedly in composition and areal extent. Recharge is by infiltration of precipitation within the basin. Natural ground-water discharge may be entirely or partially to the basin playa or to adjacent basins. Pumping in these basins is mainly from storage.

Closed basins in which more than 10,000 acres of irrigated land have been developed are the Estancia, Mimbres, and Animas Valleys. Lesser acreages of irrigation have developed in the Alamogordo-Tularosa area (Tularosa Basin), the Crow Flats area (Salt Basin), and in the Playas and Lordsburg Valleys.

Estancia Valley, Torrance County

The Estancia Valley is located east of the Sandia and Manzano Mountains. Precipitation within its boundaries recharges the ground water reservoirs which in turn discharge to the playa lakes southeast of the town of Estancia. The principal aquifer is a valley fill deposit consisting largely of unconsolidated sediments. However, locally underlying bedrock aquifers yield large quantities of water to wells.

The playa lake area is estimated to evaporate an average of about 35,000 acre-feet of water per year. This is indicative of the recharge to the basin because it is unlikely that effects of pumping have reached the discharge area.

Irrigation in the Estancia Valley was not successful until after World War II. In 1947, about 5,000 acres was irrigated and since 1951 the irrigated area has varied between 20,000 and 25,000 acres. From 1950 to 1960 water levels declined more than 5 feet under 150 square miles, more than 10 feet under 113 square miles, more than 20 feet under 28 square miles, and more than 25 feet under 14 square miles.

Animas Valley, Hidalgo County

The Animas Valley in Hidalgo County is a north-trending intermontane basin extending from near the Mexican boundary to about 20 miles north of Lordsburg. Only in its southern end is Animas Creek ephemeral. South of Animas Station the channel of Animas Creek merges with the plain of the valley and drainage continues northward as sheet flow to the playa lakes.

The ground-water reservoir in the valley fill is recharged by precipitation over the drainage basin and by a small underground flow from Playas Valley. Annual precipitation is about 10 inches and recharge probably does not exceed a few thousand acre-feet per year.

The irrigated area increased fairly rapidly from a few hundred acres in 1947 to about 11,000 acres in 1952. Since 1957 irrigation has remained steady at about 12,800 acres. Pumpage from 1950 to 1960 has averaged about 19,700 acre-feet annually. Essentially all the water used for irrigation is taken from storage because recharge to the reservoir is small compared with the amount of water pumped, and natural discharge has not been diminished. From 1950 to 1960 water levels declined more than 20 feet under 43 square miles and more than 30 feet under 9 square miles. If irrigation does not increase, water-level declines may be expected to decrease each year as more and more water flows toward the wells from distant areas.

Mimbres Valley, Luna County

The Mimbres Valley is a closed drainage basin located principally in Luna County. The unconsolidated sediments of undetermined thickness that underlie the valley floor constitute the reservoir which is recharged by runoff from surrounding mountains and by precipitation on the plains of the basin. Ground water moves generally southward and probably contributes to the flow of springs near Palomas Lake about 5 miles south of the Mexican border.

Irrigation with ground water began in the Deming area in 1908. Expansion was rapid from 1912 and by 1914 nearly 200 pumping plants were in operation. After 1918 the number of plants decreased to about 25 and not until the middle 1920's did irrigation begin to expand again. The irrigated area averaged 7,600 acres from 1930 to 1940; 16,800 acres from 1940 to 1950; 31,900 acres from 1950 to 1960; and 35,000 acres in 1960. Until 1950 the irrigated lands were located principally south and west of Deming and north and east of the Little Florida Mountains in the Lewis Flats area. From 1951 to 1953 development increased in the Columbus, Red Mountain, and Franklin areas.

From 1913 to 1940 water levels declined more than 15 feet in two areas totaling about 33 square miles, and more than 10 feet in an area of about 113 square miles in the main irrigated area around and south of Deming. In the same period water levels in the Lewis Flats area declined more than 35 feet under 3 square miles and more than 20 feet under 16 square miles.

From 1940 to 1950 water levels in the Deming and Lewis Flats areas declined more than 18 feet in two areas totaling about 4 square miles and more than 8 feet under 138 square miles.

From 1950 to 1960 water levels in the Deming, Red Mountain, Lewis Flats, and Franklin areas declined more than 30 feet in areas totaling 13 square miles, more than 20 feet in areas totaling 81 square miles, and more than 15 feet in areas totaling 162 square miles.

RIVER VALLEYS

In drainage areas containing through-flowing streams the ground-water reservoirs discharge principally to water courses and lakes of the surface drainage system. Ground water near the surface may be consumptively wasted by evaporation from the soil and be transpiration from vegetation. Locally the stream may lose water to the ground-water reservoir but reappearance is likely at some lower elevation in the system.

Roswell artesian basin, Eddy and Chaves Counties

The Roswell artesian basin lies within the Pecos River Valley. It extends from near Vaughn on the north to the Seven Rivers Hills to the south, and from the summit of the Sacramento Mountains on the west to the escarpment of the High Plains on the east. The principal area where ground water is used for irrigation extends along the west side of the Pecos River from north of Roswell southward to Seven Rivers. In this area about 117,000 acres of land is irrigated by artesian and nonartesian or shallow water, and about 10,000 acres of surface-water-right land is supplemented with ground water.

Artesian water is obtained from the San Andres formation, a limestone unit containing water under artesian conditions. Shallow or nonartesian water is obtained from unconsolidated sand and gravel fill overlying the limestone aquifer. The reservoirs are related to each other and to the water in the Pecos River and its tributaries. Source of water in the artesian reservoir is precipitation on outcrop of limestone formations west of the Pecos River. The shallow-water reservoir in the valley fill obtains its recharge principally by upward leakage from the underlying artesian reservoir, return flow from irrigation, and direct precipitation on its surface area. Before development of wells for irrigation, the basin discharged to the Pecos River through springs and accretions from the valley fill.

Since irrigation with artesian water began about 1900, artesian levels have declined about 50 feet in the Roswell area, and about 300 feet in the Artesia area. The area of original artesian flow has been reduced to a small fraction of its original size.

Leaky artesian wells and return flow from irrigation caused water levels in the valley fill to rise. Drainage works were constructed in the 1920's to prevent some lands from becoming water-logged. Development of ground water from the valley fill since 1937 has caused those water levels to decline as much as 65 feet in some local areas. Lowering of water levels has diminished the flow of many of the drains.

Natural discharge of the basin to the Pecos River before wells were constructed was about 235,000 acre-feet annually. In the last decade, ground-water discharge from the reservoir by wells has averaged more than 430,000 acre-feet per year. Rainfall, indicative of recharge, for the same period has been about 75 percent of normal. During this period discharge by wells was approximately 4 times as great as natural discharge and 2-1/2 times as great as probable recharge. Water to meet the overdraft is pumped largely from reservoir storage.

Carlsbad area, Eddy County

The Carlsbad area in the Pecos River Valley is bounded on the north by the Roswell artesian basin. As in the Roswell basin, ground water occurs in a limestone reservoir and in a valley fill reservoir. In most places the two lie adjacent rather than superimposed. The two are related to each other and to the river. Locally each yields large quantities of water to wells, the limestone generally producing water of better quality.

Irrigation wells in the limestone and valley-fill reservoirs were developed rapidly after 1945 to subjugate new lands and to provide water to supplement surface-water sources. About 4,200 acres of land is irrigated solely with ground water and about 20,000 acres of land irrigated by surface water receives supplemental ground water. Estimated pumpage from both reservoirs was about 54,000 acre-feet in 1960.

Recharge to the limestone reservoir is from precipitation on the outcrop areas and leakage from Lake Avalon. The aquifer discharges mainly to the Carlsbad Springs area and to wells which, since 1954, have pumped from 13,000 to 17,000 acre-feet per year.

Water levels in the limestone reservoir fluctuate in response to precipitation, pumping from wells, and leakage from Lake Avalon. The magnitude of these fluctuations has not been large, but even small declines are reflected by decreased flow in the Pecos River.

Declines of water level in the valley-fill reservoir east of the Southern Canal ranged from 5 to 10 feet from 1947 to 1960. Water levels in an area south of Carlsbad and west of the Canal where ground water is the only source of water for irrigation declined as much as 30 feet during the same period.

ECONOMICS OF GROUND WATER IRRIGATION

W. P. Stephens[1]

Economics has been defined as "the allocation of scarce resources among competing ends." It is easy to understand that if we had enough ground water to supply all the water desires of present and future users there would be little need for a discussion such as this. From what has been said here at this conference, it is obvious that ground water is a scarce resource and many users are competing for it.

First, I would like to discuss briefly the macro or general approach to the use of ground water for irrigation. From an economist point of view, I believe many of the decisions made by the office of our State Engineer, with regard to the Lea County basin, have been wise. The number of irrigation wells in that basin have been limited.

The cost of pumping water in Lea County in 1960 was about $6.70 per acre foot or $16.08 per acre (based on 2.4 ac/ft. per acre). In 47 years or by 2007 the cost per acre will have increased to about $30.76 per acre (table 1). This is the return per acre after all costs except water have been deducted. This could be called the economic limits of pumping. The year 2007,

Table 1. Increasing Cost of Water and Residual Returns to Water, Lea County, New Mexico[1]

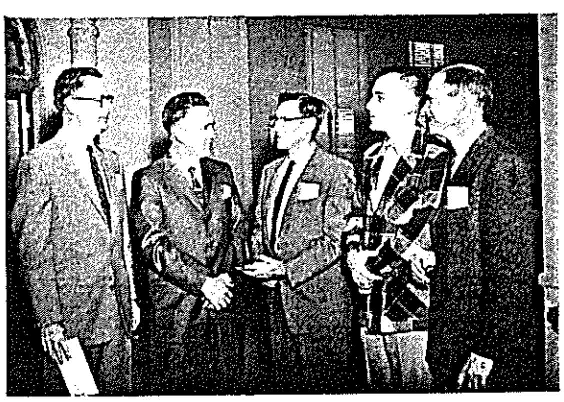
Year	Cost of Water Per Acre
1955	$14.52
1960	16.08
1965	17.64
1975	20.76
1985	23.88
1995	27.00
2005	30.12
2007	30.76[2]
2015	33.24

1/ Cole, James F., Masters Thesis, New Mexico State University, August 1960, p. 90.
2/ Residual returns to water, per acre.

1/ Agricultural Economist, Department of Agricultural Economics and Agricultural Business, Agricultural Experiment Station, New Mexico State University.

A discussion among the program members prior to the final Conference session. Left to Right: Jack Lacy, Deputy Director, Department of Development; Steve Reynolds, State Engineer; James F. Cole, Assistant to the President, N.M.S.U.; Charles C. Royall, Lawyer, Arizona State Land Department; and John H. Cuykendahl, Colorado Groundwater Commission.

Left to Right: Jay Stow, District Chemist, U. S. Geological Survey; Dean P. J. Leyendecker, N.M.S.U.; and Robert W. Stellman, Engineer, U. S. Geological Survey.



Left to Right: James W. Young, District Manager, Bureau of Land Management, Las Cruces; Claude A. Martin, District Manager, Bureau of Land Management, Albuquerque; K. A. Valentine, Professor of Animal Husbandry, N.M.S.U.; Clarke Leedy, Extension Soil Conservationist; Edward H. Wallace, District Supervisor, Extension Service.

Left to Right: Harold Elmendorf, Irrigation Engineer, Mesilla Park; George Worley, Pack Foundation, University of New Mexico; Roy Calkins, Farmer, Sacramento, N.M.; and Reverend Bruce Potter, First United Presbyterian Church, Las Cruces, looking over the State water map, on exhibit during the Conference. Hats off to Mr. Worley and the Pack Foundation for this fine educational exhibit.

when it is estimated that economic limits will be reached, corresponds very close to the estimate of physical limitations for pumping irrigation water. Physical limitations are based on estimates of present ground water supply and withdrawals during the next 47 years.

This is quite a contrast to the Texas side of the basin where well drilling is not controlled and it is very likely that both economic and physical limits of pumping irrigation water will be reached much sooner than in New Mexico.

Another general question might be asked for the dry land farmer on the east side of the state--should he put in an irrigation well? One of the first things any farmer will want to know is--how much will it cost to install an irrigation well and pumping plant? Figure 1 and Table 2 show the relation between investment in well and pumping plant and depth of pump setting.

Figure 1. Investment in Well, Pumping Plant and Depth of Pump Setting, New Mexico

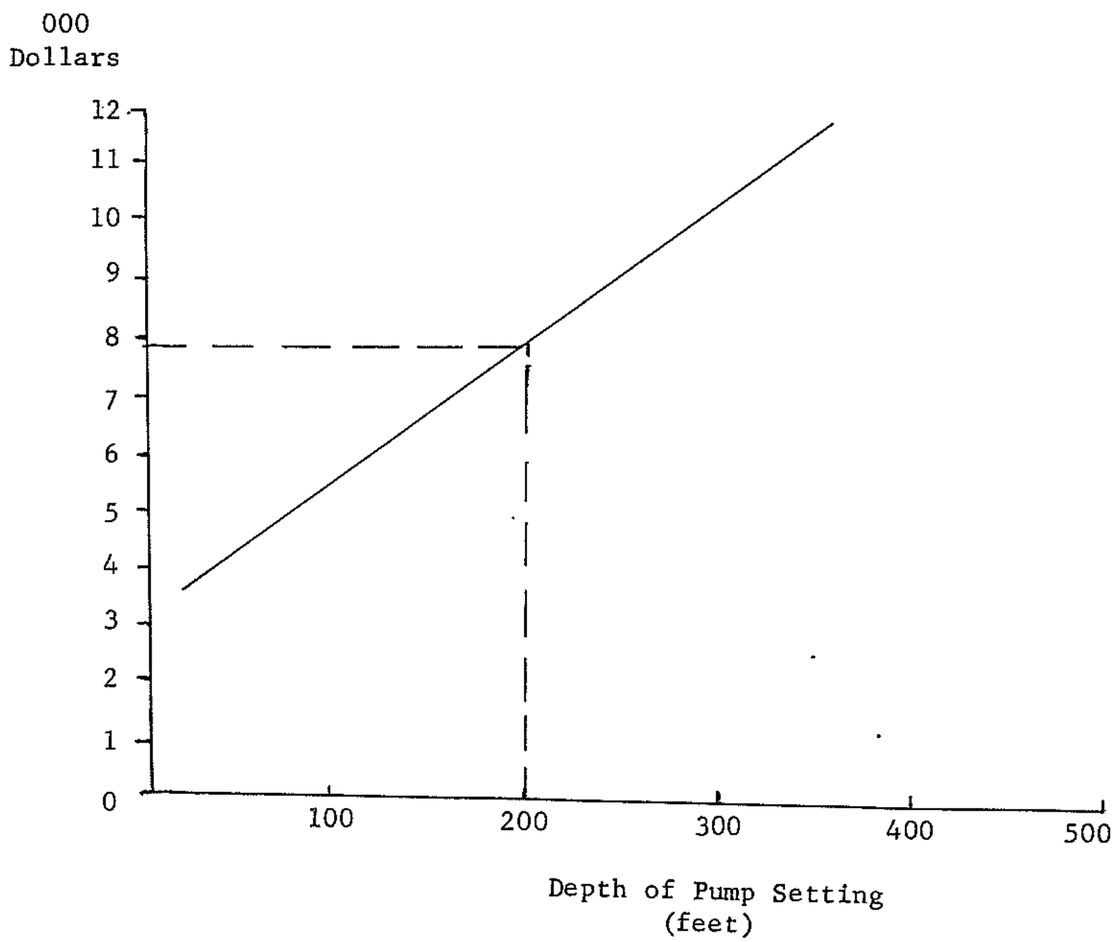


Table 2. Investment in Well, Pumping Plant and Depth of Pump Setting, New Mexico

Investment in	Group I 29 wells[1/]	Group II 32 wells[1/]	Group III 59 wells[1/]
	(Dollars)	(Dollars)	(Dollars)
Well	3088	1945	600
Pump	5355	2486	2121
Power Unit	2626	1185	1026
Total	11069	5616	3747

Depth:			
Drilled (ft.)	371	237	121
Pump Setting (ft.)	307	123	85
Lift (ft.)	277	111	77
G.P.M.	990	951	1190

1/ Group I - Curry County, Group II - Estancia Valley, Group III - Lea County.

Current estimates show that a 200 acre dry land farm in Lea County might expect a net return of $17.75 per acre. By adding an irrigation well the net income could be increased by about $14.68 per acre (table 3).

Table 3. Return per Acre from a 200 Acre Dry Land and Irrigated Farm in Lea County, New Mexico[1/]

	Per Acre $
Dry land:	
Net Income	$17.75
Irrigated:	
Net income before deducting cost of water	$48.51
Less dry land income	- 17.75
Residual return to water	$30.76
Less Current Cost of water	- 16.08
Net increase per acre	$14.68

1/ Cole, James F., Masters Thesis, New Mexico State University, August 1960, pp. 87-88

If we examine the yields of irrigated and dry land wheat and grain sorghum in Curry County, we find substantial differences (table 4). For grain sorghum there is a yield difference of 2748 pounds. Using a price of $1.75 per hundredweight the increase return would be $48.09. If we subtract out the cost of pumping water, we find a net increase in returns per acre of $29.65 when pumping with natural gas and $19.39 when using butane (table 5).

Table 4. Yield of Sorghum and Wheat, Curry County, 1957-60 Average

	Irrigated	Dry	Difference
Sorghum - pounds	3881	1133	2748
Wheat - bushels	33	14	19

Table 5. Costs and Returns Per Acre from Irrigation, Curry County

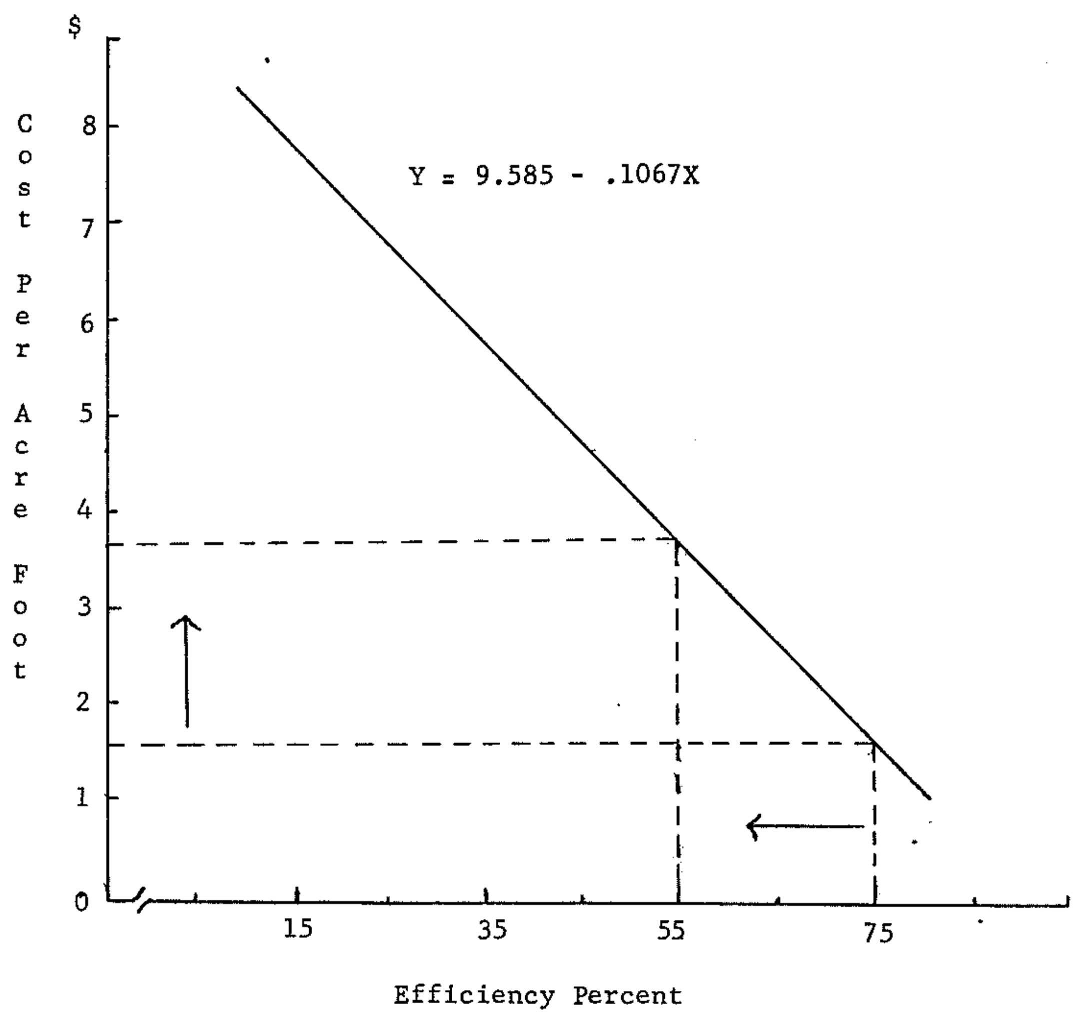
Sorghum Grain:		
Increase in Returns		$48.09
Cost of Water:		
Natural Gas	(2 acre feet)	18.44
Butane		28.70
Wheat:		
Increase in Returns		$34.20
Cost of Water:		
Natural Gas	(1.4 acre feet)	13.83
Butane		21.53
Cost of Water Per Acre Foot:		
Natural Gas		$ 9.22
Butane		14.35

With wheat at $1.80 per bushel the net increase per acre after cost of pumping is deducted would be $20.37 using natural gas and $12.67 using butane.

I would like to examine now some of the economic factors of irrigation at the farm level. One of the important factors that effect the cost of pumping irrigation water is the efficiency of the pumping plant. Over-all efficiency of the plant is determined by multiplying the efficiency of the pump by the efficiency of the power unit. For example, if the pump is 70 percent efficient and the power unit 50 percent efficient the over-all plant efficiency would be (.70 X .50) 35 percent.

Figure 2 shows that for every 1 percent change in efficiency for electric pumping plants in Lea County the operating (or cash) cost increase by 10.67 cents (Y = 9.585 - .1067X). This means that if the efficiency dropped from 75 to 55 percent the operating cost per acre foot would increase from $1.58 to $3.70.

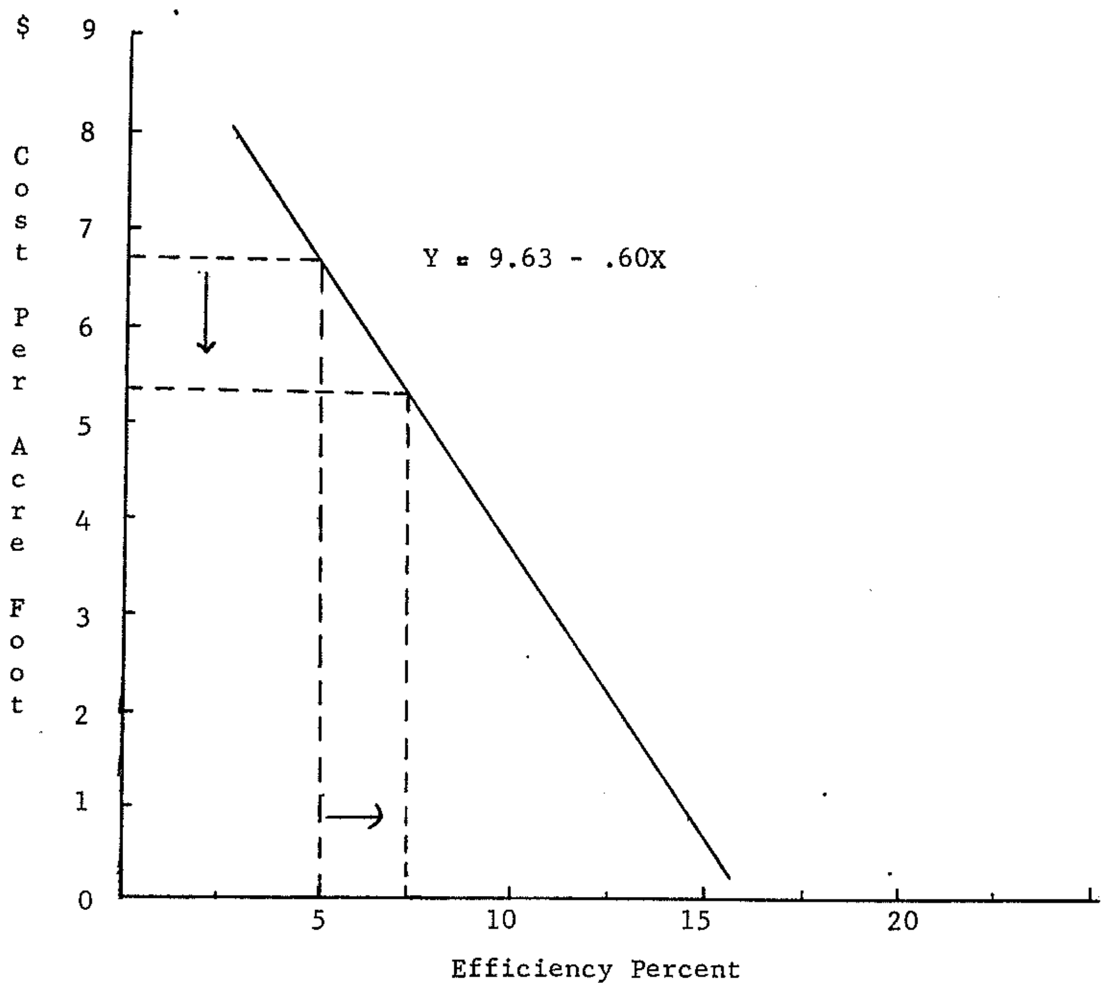
Figure 2. Operating Cost Per Acre Foot and Efficiency, Electric Power--Lea County



Since internal combustion engines are not as efficient as electric motors, we find that small changes in efficiency (of power units using butane or natural gas) are associated with rather large changes in costs. For every 1 percent change in efficiency for butane using plants in Lea County, there was a change in operating costs of 60 cents (Y = 9.63 - .60X). For example, if plant efficiency increased from 5 percent to 7½ percent (2.5%) operating costs per acre foot would decrease from $6.75 to $5.25 ($6.75 - (2.5 X .60) = $5.25).

Another factor that influences the cost of pumping irrigation water is the discharge of the well in gallons per minute (G.P.M.).

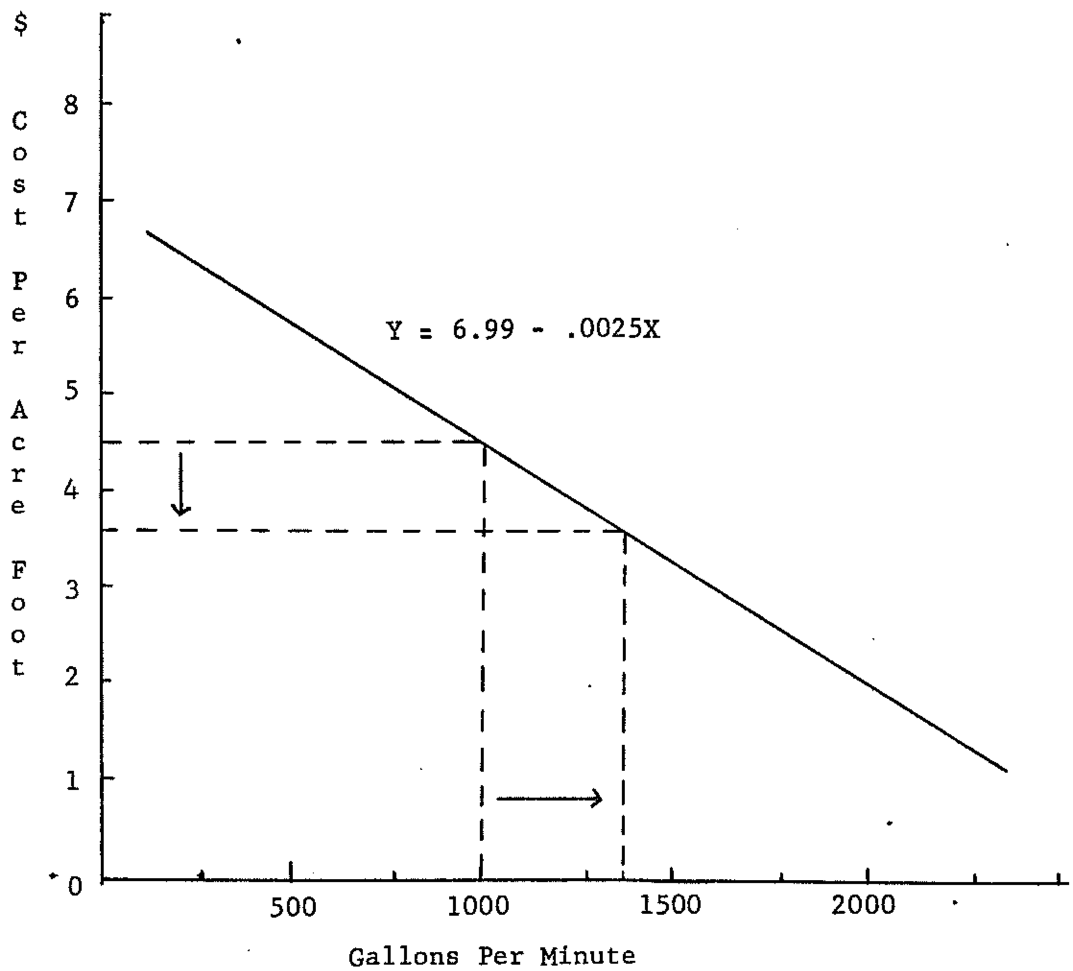
Figure 3. Operating Cost Per Acre Foot and Efficiency, Butane--Lea County



We found in Estancia Valley for electric power units that for every 100 G.P.M. increase in discharge the operating cost per acre foot decreased by 25 cents (Y = \$6.99 - .0025X). If G.P.M. discharge increased from 1000 to 1400 the operating cost per acre foot decreased from \$4.50 to \$3.50 (\$4.50 - (400 X .0025) = \$3.50).

Findings in Curry County also indicate a definite relationship between total cost per acre foot and G.P.M. discharge.

Figure 4. Operating Cost Per Acre Foot and Discharge of Well Electric Power--Estancia Valley



For well pumping less than 400 G.P.M. the loss was about $16.00 while for those pumping over 800 G.P.M. the total cost per acre foot was just about half as much.

Table 6. Total Cost per Acre Foot and G.P.M., Curry County

G.P.M.	Cost
400 and less	$16.11
401 - 600	14.02
601 - 800	10.02
801 and over	7.99

The number of hours a pumping plant operates during the season affects the cost per acre foot. In general the more hours a plant operates during the season the lower will be the costs (table 7).

Table 7. Total Cost per Acre Foot and Hours Operated, Curry County

Hours	Cost
1900 and less	$12.09
1901 - 2500	11.76
2501 and over	8.94

Acre feet pumped per season is really a combination of the hours operated and G.P.M. discharge of the well.

It was found in Estancia Valley that plants pumping 50 acre feet per year had a loss almost three times that for plants pumping 400 acre feet (table 8).

Table 8. Total Pumping Cost per Acre Foot Estancia Valley

Acre Feet Pumped	Cost
50	$15.69
100	9.86
200	6.94
300	5.97
400	5.49

Cost of pumping is also affected by the kind of fuel used. This depends primarily on the cost per unit and varies in different areas of the state.

Findings in Curry County indicate that cost of pumping with natural gas is considerably less than with butane.

Table 9. Total Cost of Water and Kind of Fuel, Curry County

	Natural Gas	Butane
Hours run	2442	2246
Cost per hour	$1.15	$1.58
Per acre foot	322	263
Cost per acre foot	$8.68	$13.45
Cost per acre foot per foot of lift	2.74¢	4.71¢

Table 10. Annual Cost per Well, Curry County

Operating Cost	Natural Gas	Butane
Fuel	$ 892	$1,982
Repairs:		
Pump-Well	223	205
Motor	180	166
Lubrication & Oil	100	74
Labor (Servicing the plant)	40	35
Total	$1,435	$2,462

In many instances farmers can do something about the factors affecting the cost of pumping. However, we still hear complaints that cost of irrigation water is high -- I say this is all relative, and after you examine Table 11 I think you will have to agree that "Water is Plenty Cheap."

Table 11. WATER IS PLENTY CHEAP

Cost - One Acre Foot	
Pump Irrigation	$6.00
City Water	$195.00
Saline Water (conversion)	$651.00
Paid for Water in Dallas, 1956	$130,157.00
"Old Grand Dad"	$10,182,156.00

ANALYZING PUMPING TEST DATA

F. X. Bushman[1/]

It is difficult to put into a single phrase the idea that by means of a pumping test a great deal may be learned about an aquifer, a water-bearing formation from which ground water may be obtained through wells. The name applied to this type of quantitative method is aquifer performance test--or simply aquifer test. This distinguishes the aquifer test from a simple pumping test. The latter provides nothing more than the water levels in the well at each of several production rates, to aid in selecting a pump which will perform satisfactorily in the particular well. In many parts of the Rio Grande Valley, for example, the simple pumping test meets the needs of driller and owner, and probably neither would consider the prolonged pumping generally required in the aquifer test to be economical.

Why do we spend time and money learning about the aquifer characteristics? We want to know the hydraulic properties because it is possible to use these characteristics to predict future behavior of water levels in the aquifer. By using mathematical formulas with a given set of values, with assumed or expected pumping conditions and an assumed or predicted time period, we can calculate future water levels in the aquifer. And the calculation of water-level changes allows us to decide whether or not we can afford to operate under those conditions. We can answer such questions as: Will the pumping levels drop below economic pumping lifts? Will the levels drop sufficiently for parts of the aquifer literally to dry up? These are questions that constantly confront large users of ground water. Quantitative methods are also used to learn about discharge from the aquifer, recharge to the aquifer, leakage from other water-bearing beds, and infiltration from surface bodies of water. Among the many other useful applications of the aquifer performance test analyses are some relatively simple problems; for example, how much interference will we have between wells in a particular well field? If a well field is located in an aquifer for which the supply of water is very abundant, the interference may actually be much more important to the operation than the long-range predictions. Interference as used here--or rather as used in groundwater studies generally--is the drawdown in one well caused by pumping another well. Obviously, if a number of pumping wells are located so that each is within the radius of influence of each of the others, that part of the drawdown caused by the

1/ Groundwater Hydrologist, New Mexico Bureau of Mines and Mineral Resources, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

mutual interference may increase pumping costs to the operator. This would indicate a need for an engineering study to determine the most economical spacing, keeping in mind that greater spacing requires more pipelines, more electric or gas lines, and perhaps more property. Initial cost must be considered together with operating costs.

To help in understanding what is meant by aquifer testing, let us consider first what happens when we pump a well which taps an unconfined aquifer; that is, an aquifer in which the surface of the water is exposed to atmospheric pressure. The water table drops and air replaces water in the voids in, say, 20 percent of the dewatered volume. The gradient, or slope of the water table toward the well, is created causing water in the aquifer to move toward the well. Careful observation of the behavior of the water levels in near-by wells during pumping will permit us to evaluate the coefficient of storage and the coefficient of transmissibility, two terms which are most important in quantitative work. The coefficient of storage, S, is a measure of the amount of water obtained from storage during pumping, and the coefficient of transmissibility, T, is a measure of the rate at which water will flow through the aquifer. (Since the pore spaces retain some water, part of which continues to drain slowly over a period of time and part of which is retained, this description is an over-simplification.)

For a confined aquifer--that is, an artesian aquifer--the concept of obtaining water from storage may be slightly more difficult to visualize. The artesian aquifer has confining beds and the water level in a well penetrating it will rise above the top of the aquifer. When we start pumping we know that as we continue to take water out of the well the aquifer is still saturated; it is still full of water. We are also aware that at some distance from the well the conditions that existed before pumping have not changed. Where, then, did the pumped water come from? First, a very small part of it came from expansion of the water itself as the pressure was reduced near the well. The decrease in pressure also reduces some of the support of the skeleton of the aquifer and the compaction occurs. This is true also of less permeable beds, lying within the aquifer and some water is squeezed out of these beds. The storage coefficient for an artesian aquifer is very small compared to the coefficient for an unconfined (water-table) aquifer. By contrast with the water-table aquifer described before, the entire thickness of the artesian aquifer within the area of a pressure decline contributes water from storage. Of course, just as with the artesian aquifer, some water is released from storage by compaction in an unconfined aquifer below the water table, but this factor is so small that it usually has been neglected. In a very thick aquifer it has been shown to be important.

As pumping continues in either a water-table or artesian aquifer, the effects of pumping continue to spread until sufficient natural discharge or formerly rejected recharge is intercepted to offset the quantity pumped. Leakage through adjacent beds may supply the recharge. More recently, Hantush has found that partial penetration, particularly of very thick aquifers, tends to cause the water levels in observation wells to behave similarly to those resulting from recharge.

In medicine, when the doctor has diagnosed your case, he writes his diagnosis in some mysterious symbolic language that probably most of the old Romans would have had trouble deciphering. In ground-water work, the hydrologist does something very similar. He probes around to find all the facts that apply to a particular situation, then applies a mysterious formula or two (really more complex than mysterious) from which he draws conclusions about the values of the coefficients of transmissibility and storage.

Many of the facts he obtains are gathered by conducting aquifer performance tests. These data, generally discharge measurements and water levels measured periodically in one pumped well together with water levels measured in one or more observation wells, are used to obtain particular solutions to equations of ground-water flow. There are innumerable conditions under which ground water can occur, and for each situation the hydrologist, geologist, or engineer must be aware of the limitations of the formula he has decided to use. He must understand the assumptions that were made when the formula was derived; such simplifying assumptions have to be made for any derivation to keep from obtaining an equation which would simply be too cumbersome to apply.

A little more than a hundred years ago, in 1856, a Frenchman named Henry Darcy published the law of flow which has since come to bear his name. A few years later, in 1863, DuPuit, also a Frenchman, applied Darcy's law to well hydraulics, using an ideal example of a well located at the center of a circular island. In 1906, Thiem, a German, modified DuPuit's work to apply to more general problems. From then until 1935, a number of investigators presented modified forms of the DuPuit relationship. These are all forms of the "equilibrium method" in which the rate of discharge of the pumped well is equal to the rate of flow of water toward the well, for all concentric cylinders about the well. But in 1935, C. V. Theis, of the U.S. Geological Survey, Ground-Water Branch, published a paper entitled The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. This nonequilibrium method, as it has come to be known, contains an exponential integral, a little mathematical complexity which made it fairly difficult to solve. Theis suggested a graphical method to Jacob and Wenzel, both of whom subsequently published descriptions of such a method in 1940 and 1942, respectively.

In the Theis nonequilibrium method, a number of assumptions were made in its derivation. It was assumed that the aquifer was infinte in extent--in a practical sense, this means that it covered a very large area compared to its thickness; it was assumed that the hydraulic properties of the aquifer were the same in all directions; it assumed that water was released instantaneously from the formation. Since Theis' publication in 1935 there have been numerous contributions, some of which modified the nonequilibrium method, some of which presented methods and formulas for handling situations other than the ideal. Techniques have been developed for dealing with boundaries of aquifers, partial penetration of the aquifer by wells, leakage into or out of the aquifer through the confining beds, special recharge or discharge conditions, effect of sloping beds, effect of varying thicknessess, and combinations of these. Several of these conditions will usually be present, and the practicing hydrologist must understand the conditions if he hopes to define the ground-water situation with reliability.

The lower of the two curves in Figure 1 shows the behavior of water levels in a pumped well in an ideal aquifer. When pumping starts the water level drops rapidly, then the rate of lowering decreases as pumping continues. The upper curve in Figure 1 shows water levels in a typical observation well, which in this instance is located 120 feet from the pumped well. Shape of the curves will vary depending on the conditions of pumping and on the aquifer characteristics. Note that these curves have been plotted on plain coordinate graph paper and that each unit is represented by an equal spacing.

In Figure 2 the same observation well data used in Figure 1 are shown plotted on log-log (logarithmic scale) graph paper for a type-curve graphical solution of the Theis nonequilibrium formula. The drawdown (change in water level) is plotted on one scale, and time, or rather the reciprocal of time, is plotted on the other scale. Note that equal spacings on a logarithmic scale represent the logarithm of the units plotted and not the units themselves. Each cycle represents 10 times the previous cycle. A type-curve is plotted on the same scale log paper, in which W(u), the well function containing the exponential integral, is plotted against tabulated values of u, which contains distance, time and the coefficients of transmissibility and storage. The field data generally are plotted on semitransparent tracing paper which is positioned above the type-curve until the "best-fit" position is obtained, keeping the axes of both sheets parallel. The coordinates of any point common to both sheets are read and these values inserted into the equations to obtain the formation constants.

The Jacob straight-line modification, in common use, simplifies the analytical procedures for the ideal aquifer since after an initial period of pumping, the drawdown vs. time plot becomes a straight line on semilog graph paper. In Figure 3 the drawdown is plotted on the arithmetic scale as in Figure 1 and time is plotted on a logarithmic scale as in Figure 2. In an ideal aquifer the water level continues to decline along the straight line. The slop of the straight line portion is used in an equation to evaluate the coefficient of transmissiblity, T. The intercept of the straight line extrapolation with the zero-drawdown line is used to obtain the coefficient of storage, S.

The following figures illustrate aquifer test results for some of the field conditions other than the ideal:

The curves in Figure 4[1/] illustrate variations in the time-drawdown relation that will occur for observation wells partially penetrating an aquifer. Curve 2 indicates that the water level would behave quite differently for one-fourth penetration than for complete penetration, as shown by Curve 1, the Jacob straight-line modification. Curve 2 for an infinitely thick aquifer illustrates a condition in which water-levels would appear to approach equilibrium. Similarly-shaped curves may be obtained when recharge is induced as a result of pumping, or when leakage occurs through confining beds, illustrating the importance of knowing the geologic conditions in the area.

In Figure 5 are shown log-log and semilog plots of a partial penetration analysis of an aquifer test. The log-log analysis developed by Hantush involves matching field data with a family of type-curves as shown in Figure 6.

Leakage through a confining bed is shown in Figure 7. Note here that the shape of the curve is somewhat similar to that developed by partial penetration. Under conditions of pumping, the original head relationship between upper and lower aquifer is changed and leakage occurs. The quantity leaking through a single square foot of the base of the confining bed may be very small, but when multiplied by the area of influence of the pumping well this quantity

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1/ Figures 4 through 8 are from published works of Dr. Mahdi S. Hantush, formerly of the New Mexico Institute of Mining and Technology, now on the staff of the University of Baghdad.

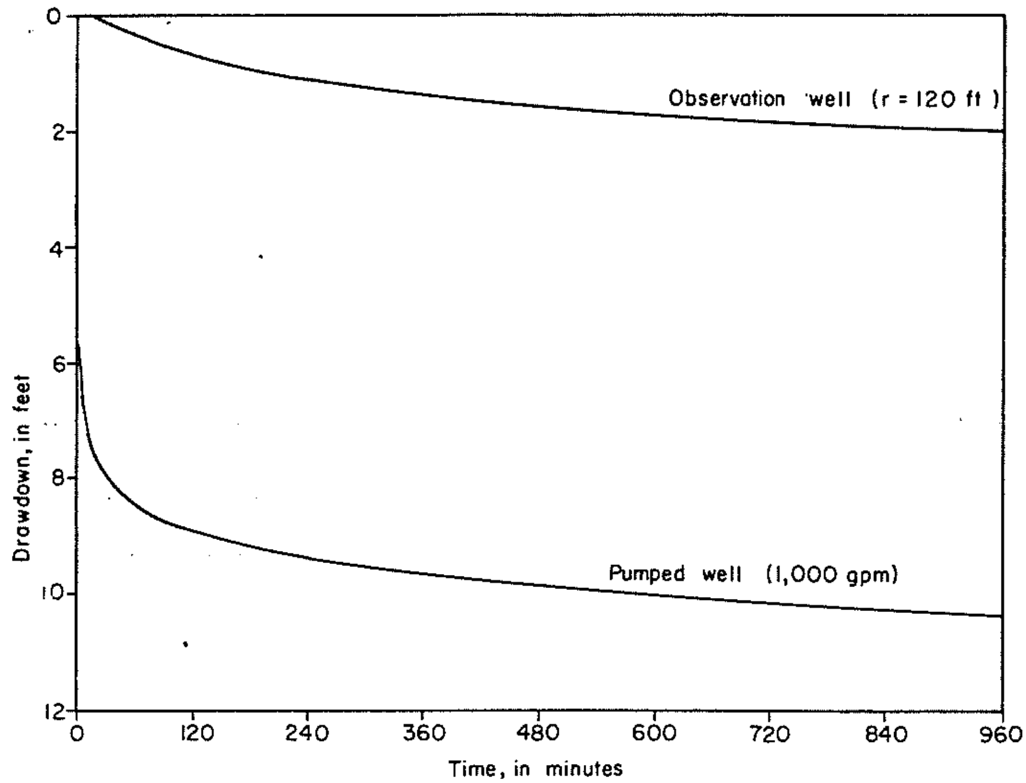

Figure 1. Water levels vs. time. Observation well at a distance of 120 feet from the pumped well.

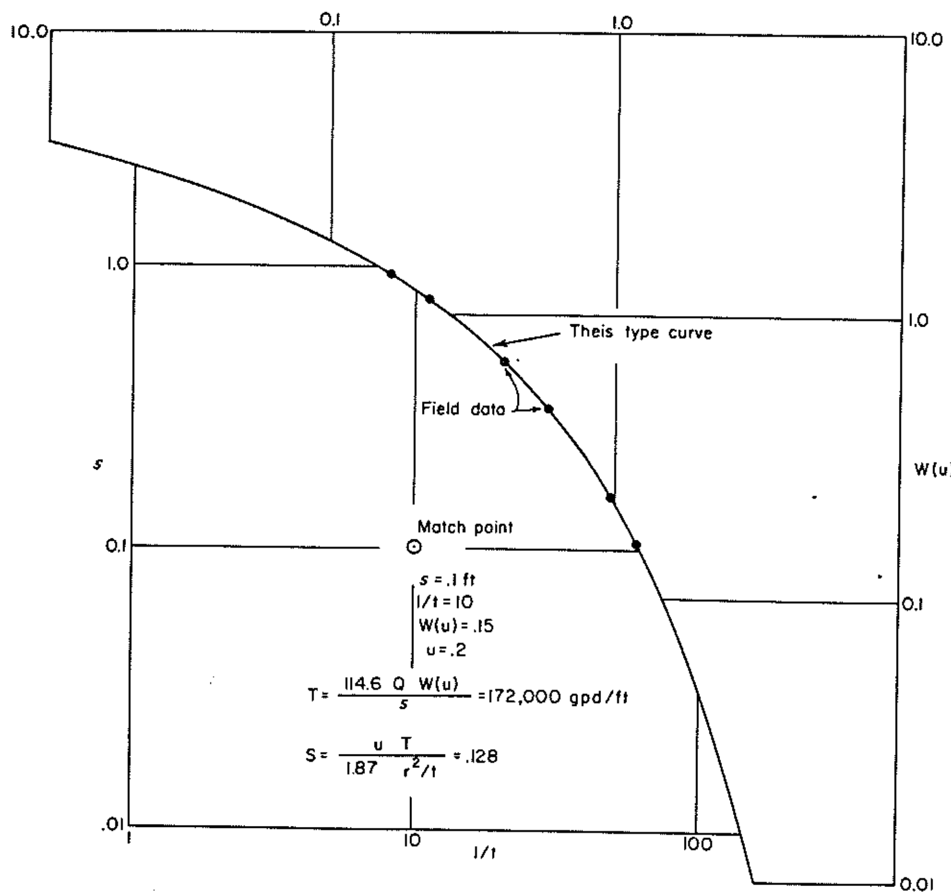

Figure 2. Theis type curve "matched" with field data on log-log plots. Same data as shown in Figure 1.

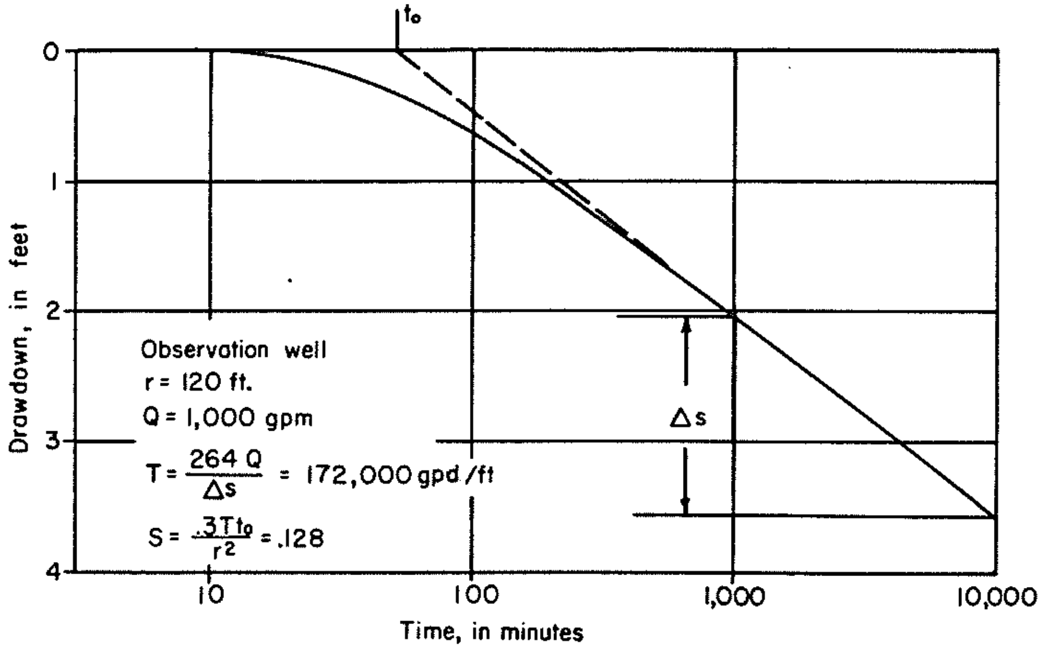

Figure 3. Jacob's modified straight-line plot. Same data as shown in Figures 1 and 2.

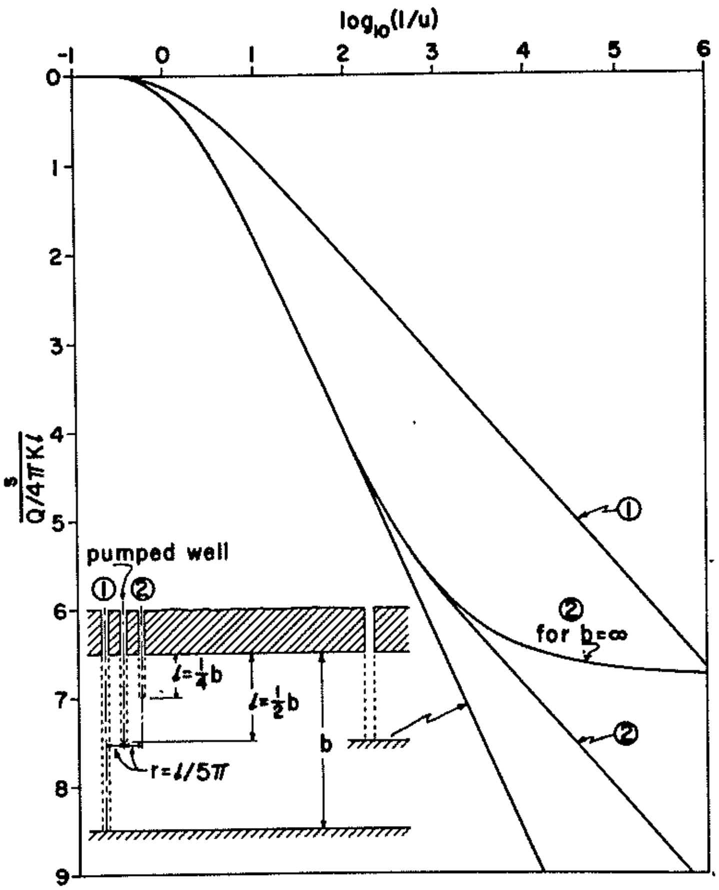

Figure 4. Time-drawdown variation in partially penetrating wells.

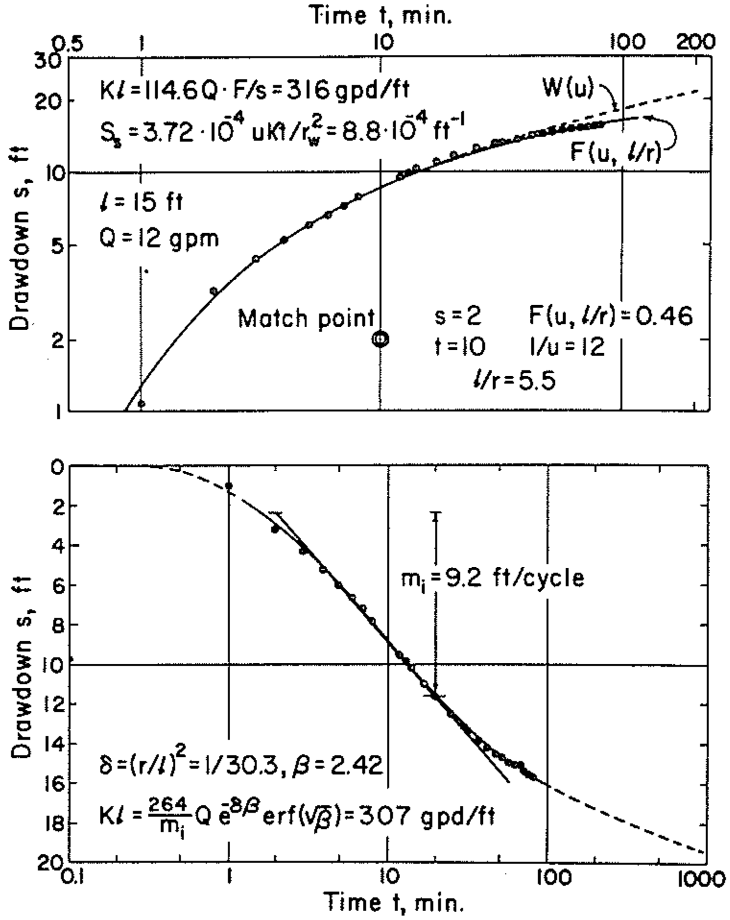

Figure 5. Analysis of partial penetration, observational data.

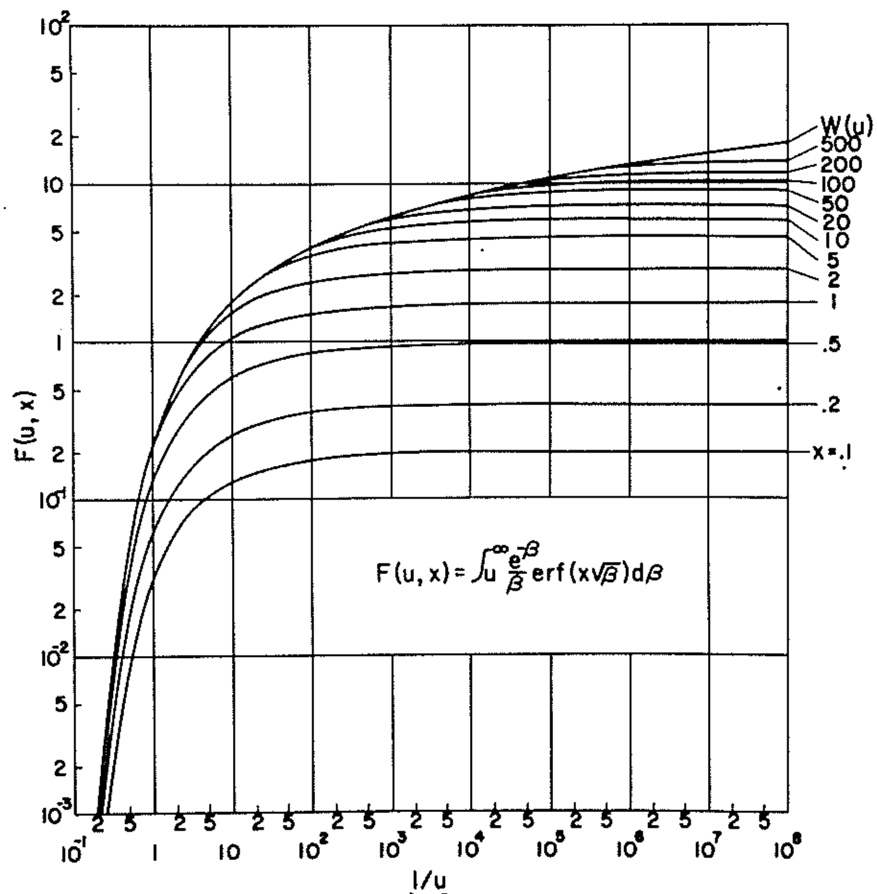

Figure 6. Type-curves of the function F(u,x).

is very large and, as indicated by the flattening of the water-level curve, a condition may be reached when no further drawdown will occur in wells penetrating the pumped aquifer.

Yet another condition which occurs frequently and which results in data varying from the behavior of water levels in the ideal aquifer is a very thick water-bearing formation with the lower part responding like a semipervious layer. Permeabilities often decrease with depth because of compaction resulting from the added weight of the greater thickness of deposits.

Figure 8 is included to show the complexities arising from sloping beds.

It is important that aquifer conditions must be included in the analyses of aquifer tests. Without such recognition it is obvious that analyses may be misleading and incorrect to such an extent as to cause gross errors in the prediction of future conditions.

This is not an attempt to sell, either directly or indirectly, the idea that quantitative analysis is the only tool of value in ground-water hydrology. Every discipline that can contribute even the smallest amount of knowledge in this work must be used. Without a doubt, the geology must be understood to appreciate the occurrence of ground water. Geophysics can help tremendously, and soil science will help toward understanding the movement in the zone above the water table so that the recharge mechanism will be more readily explained. The ground-water hydrologist must look for help from many of his colleagues and must himself become a sort of jack-of-all-trades.

Under the right conditions, or any conditions, with the right technique and proper analysis, the ground-water situation can be adequately defined. Many of the conditions in the field are so complex that workable methods have not yet been derived. In some instances, we still do not have the right technique and are using other techniques with the realization that although they may not be entirely accurate, the answers found are nearly always better than mere guesses.

The selected reference list, though by no means complete, includes some of the recent developments in ground-water hydrology.

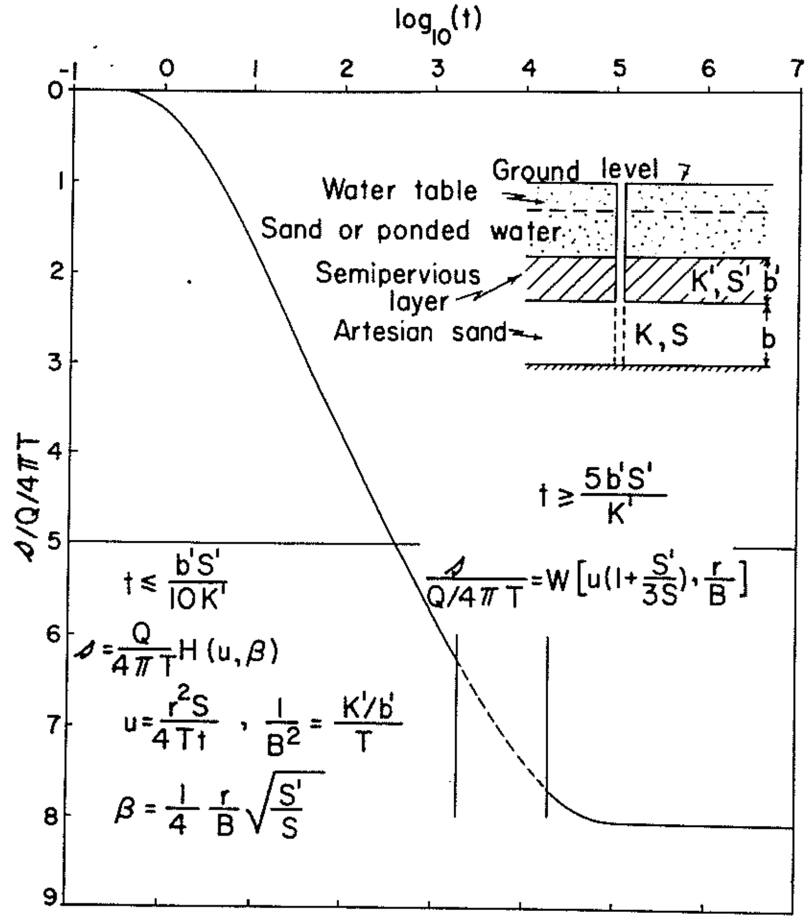

Figure 7. Analysis of leaky aquifer observational data.

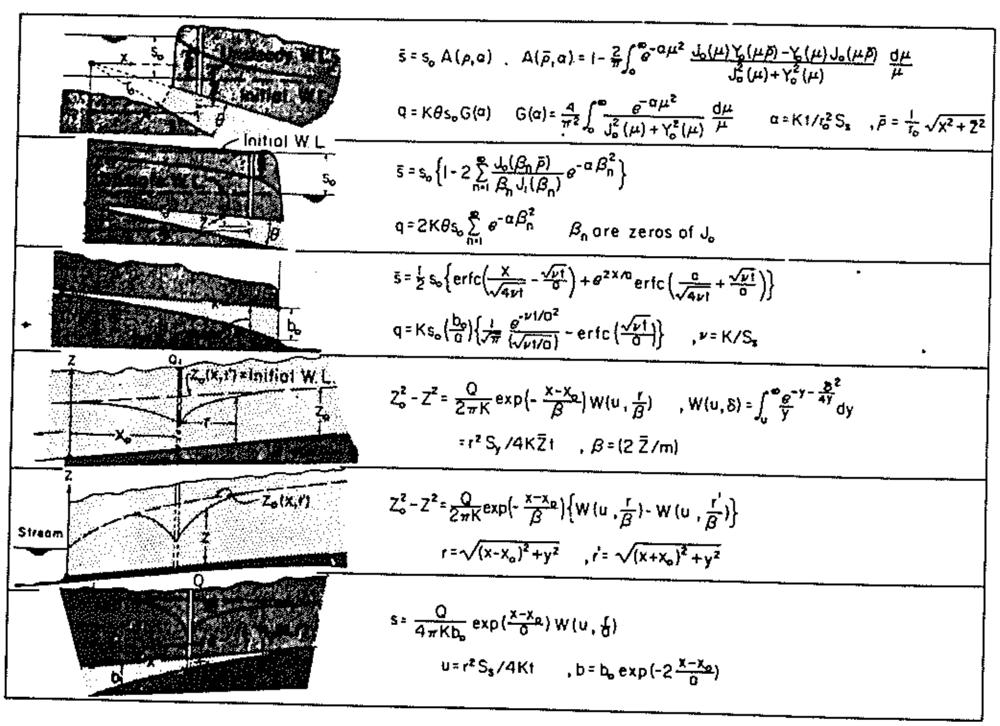

Figure 8. Flow in sands of nonuniform thickness.

Selected References

Bruin, J., and Hudson, H. E., Jr. (1955) Selected methods for pumping test analysis, Illinois State Water Surv. Div., Report Inv. 25.

Butler, S. S. (1957) Engineering hydrology, Englewood Cliffs, N.J.: Prentice-Hall, Inc.

Hantush, M. S. (1956) Analysis of data from pumping tests in leaky aquifers, Trans. Am. Geophys. Union, v. 37, p. 702-714.

-------(1957) Nonsteady flow to a well partially penetrating an infinite leaky aquifer, Proc. Iraqi Sci. Soc., v. 1, p. 10-19.

-------(1960) Modification of the theory of leaky aquifers, Jour. Geophys. Res., v. 65, n. 11, p. 3713-3725.

-------(1961) Drawdown around a partially penetrating well, Jour. Hydraulics Div., Proc. Am. Soc. Civil Eng., HY 4, 2964.

-------(1962) Flow of ground water in sands of nonuniform thickness; part I, Flow in a wedge-shaped aquifer; part II, Approximate theory; part III, Flow to wells, Jour. Geophys. Res., to be published.

Jacob, C. E. (1940) On the flow of water in an elastic artesian aquifer, Trans. Am. Geophys. Union, v. 21, p. 574-586.

Theis, C. V. (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage, Trans. Am. Geophys. Union, v. 16, p. 519-524.

Todd, D. K. (1959) Groundwater hydrology, New York: John Wiley & Sons.

Wenzel, L. R. (1942) Methods for determining permeability of water-bearing materials, U. S. Geol. Surv., Water-Supply Paper 887.

Wisler, C. O., and Brater, E. F. (1951) Hydrology, New York: John Wiley & Sons, ch. 7.

ELECTRICAL ANALOG MODEL FOR ANALYZING WATER-SUPPLY PROBLEMS

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The goal of all types of management is to improve or obtain maximum benefits from resources for the society in which we live. This role of management is much the same no matter what resource is concerned. Management of mental or physical capabilities of people, of factories producing goods, of farm land, of minerals dug from the earth, has the improvement of society as its ultimate goal.

A given resource will be used effectively only if the effort required to shape the resource into a useful product is less than society is willing to exert so as to gain the product. We might illustrate this by citing the simple act of driving a nail. A nail could be driven with a rock--a piece of iron ore, for example. But it is more convenient to process the iron ore and construct from it a hammer to simplify the chore of driving a nail. The conversion of iron ore to a particular shape and chemical characteristic is a fundamental management decision. The advantage to be gained in using the hammer outweighs the effort required to make the hammer, and therefore it is common practice to drive nails with hammers rather than with chunks of rock. Nearly every facet of our society has developed from such choice--or management.

The term water management is being seen in print and heard in conversation more frequently throughout the country as competition for water increases. Embodied in this term are all the frustrations and hopes of every water user. Some, frustrated by a water shortage, hope that water management will reduce or eliminate such shortages. Those struggling with deteriorating water quality hope that water management will somehow put some sparkle back in the streams. People using large quantities of water for economically marginal production hope water management will reduce their water costs, thus increasing the economic yield from their facilities. These are but a few examples of the many difficult tasks assigned to what is so often blithely called water management. I use the word "blithely" here, because it now seems to be more fashipnable than practical to approach the solution of many water-supply problems by improved water management.

To be effective, management decisions must be founded on fairly complete information of two different kinds: (1) the demands of our society, and, (2) the limits and characteristics of our resources under natural conditions and under conditions that might be created by human effort. Without adequate information of this type, people cannot judge whether a given resource can be applied effectively in a given way for improving society.

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In the field of water management, we have the same basic need for information on the demand and characteristics of supply. However, the issues are not easily defined. Many water-development plans are judged by the "cost-to-benefit ratio"--philosophically a very elementary means for judging if a proposed water-development plan will actually be of benefit to society. If all plans could be evaluated completely by such a means, there would be few unresolved questions in water management. Natural conditions are invariably changed by man's use of water and, just as invariably, it is impossible to place a realistic price tag on a tumbling fish-laden mountain stream, on the serene beauty of a lake, or on the waters in so-called "unused" streams coveted by people in another drainage basin.

Because many of the changes in water distribution arising from full development of our water resources cannot be defined in terms of dollars and cents, water-management decisions must be founded on examination of a curious combination of economics, artistic appreciation for the beauty of the natural landscape and, perhaps less ideally, human emotions. Most of the framework for decision-making in water management is founded upon the so-called common law, which has resolved many of the basic and diverse artistic and emotional attitudes of men. The more tangible economic inequities arising from water use are also arbitrated in the courts by procedures defined in the common law.

The common law, as applied, might be visualized as a rather formal expression of the way people feel their society should function. In the construction of regulatory water laws, the artistic and emotional attitudes of men are reinforced by excerpts from the technology of hydrology. Thus, we see water management through legal process as being at least partly dependent on our understanding of the characteristics of the resource.

Economic studies made to supply management with information are more directly based on an understanding of resource characteristics than are regulatory laws.

It is clear that without an adequate understanding of the hydrologic system, effective water management cannot become a reality. Hydrologic information includes data on the occurrence of water, and data on its economic and aesthetic significance to the water user. Data on the occurrence of water help define the resource; data on significance help define society's need for water. Keeping in mind that effective water management must be based on both these types of data, the remainder of this talk will be devoted to defining the water resource.

Field studies of the occurrence of water generally are divided into the following three categories: precipitation and other climatic factors, water on the land surface, and water below the land surface. Man has had but very little success in deliberately controlling the climatic factors. However, analysis of climatic data collected over a considerable period of time allows the hydrologist to make reasonably accurate estimates of the amount of water that may be supplied from precipitation in the future. Among many other uses, such information is also applied to help describe the occurrence of water naturally on the land surface and underground as afforded by precipitation, uncontrolled by man.

Detailed knowledge of the occurrence of surface and ground water as created by climatic factors alone is of relatively small importance to water management. Management is concerned with redistributing water from its natural habitat to points where it can be used most effectively by man. Therefore it is equally important for management to understand how the redistribution of water is restricted by environmental factors, or how it may be improved by taking advantage of natural circumstances existing on and beneath the land surface. If, for example, a stream basin has a topography unsuitable for reservoir construction, environmental factors preclude surface storage of runoff for use during dry periods. If the porous rocks beneath this basin are highly permeable, the excess runoff during storm periods might be stored temporarily underground. These and many other uses of the environment in water development are well known to all of us.

It is evident that the environmental factors must be clearly defined before planning of large-scale water developments can be completely effective. General-purpose hydrologic studies already fill a part of this need for management data. Such studies have been made continually for many years in most areas of the United States to provide a general background of hydrologic data useful in planning almost any practical water development. Hence an immense store of information on water conditions is now available. More intensive studies made selectively during investigation of specific water-development projects have also contributed to the store of hydrologic data.

The great bulk of this information is in the form of individual measurements, such as of streamflow, discharge from aquifers, water stages, and the like. It is common practice to appraise the natural occurrence of water by analyzing there measurements. For example, we are aware that large groups of individual stream-flow measurements can be analyzed to find the probable frequency of floods, and the expected rates of discharge over selected time intervals. Analyses of this type are comparatively easy to accomplish--the hydrologist need only observe what has happened in the past, then apply his analysis with confidence to the future--provided man's use of water will not appreciably rearrange the water distribution naturally afforded by climate.

However, a fully developed water resource does not function according to the whims of nature. Indeed, the whole point of water control by man is to make water available for his use even when natural factors, uncontrolled by man, do not provide an adequate supply. Therefore, analysis of basic hydrologic information must be enlarged from emphasis on simply learning about the natural occurrence of water. As water development becomes more and more comprehensive, it becomes increasingly important to know accurately how the environmental factors can be changed and utilized by man so the natural distribution of water will be modified adequately to meet the demand.

Perhaps one of the most difficult problems faced by anyone undertaking such an approach is the problem of making predictions that indicate how the manipulation of environmental factors will affect or improve water availability. Because both the amount of water available to the system and the water demand are highly variable with time, predictions should foretell variations in the water supply with respect to time likely to occur as a result of a given development plan. Such predictions make management aware of the limitations on water supply inherent in proposed developments and, before construction begins, permit direct comparisons between the expected demand and the proposed managed supply.

If all pertinent factors in the hydrologic system remain constant as time passes, the system is said to be in the steady state. Such a system can be analyzed, but it is not ordinarily a simple matter to do so. Streamflow changes continually, and it is only rarely viewed as being in the steady state. On the other hand, for analytical purposes ground-water flow is frequently assumed to occur in the steady state. However, in a fully developed system ground-water flow is also changing continually and therefore it cannot be considered to be in the steady state any more logically than can surface water. It has been my belief that these seemingly opposite approaches to analyses of surface- and ground-water systems have their foundation in the relative difficulties of computation. Surface-water flow can be viewed as taking place along a single line in space, which represents the stream channel. Thus surface flow, varying with time, can be described by functions of only two dimensions--length and time. In most aquifers ground water flow is not confined to a long narrow channel but is free to move in any direction. To simplify our concept of ground water flow, we generally assume that it moves horizontally. To analyze even this simplified flow system requires two spatial coordinates for steady flow. Thus, mathematically it is just as difficult to study a highly idealized steady ground water flow as it is to investigate nonsteady surface flow fairly accurately.

Water distribution on and beneath the land surface is dependent on many factors. Thus, accurate predictions of the response of the hydrologic system to an impressed change in the pattern of water distribution are difficult to make. Most system analyses are performed on theoretical models which are very simple versions of the systems observed in the field. In all cases a simplification and consolidation of the myriad of detail observed is both necessary and feasible for making accurate predictions of response. However, accuracy is often sacrificed because the analytical difficulties posed by the problem are so great that the investigator simply "gives up." In such circumstances, the system generally is idealized to a form simple enough that the ordinary analytical techniques can produce a prediction of system response without undue expenditure of time. In the extreme, this does not produce a prediction of the response in the system we have tried to simulate--too often the idealized system we have concocted bears but slight resemblance to the field system, and the predictions made from the idealized system are not applicable in practical water management.

The technique most often applied by the hydrologist for making predictions involves selecting or deriving an equation which relates impressed change to the system characteristics and system response. The more complicated these factors are, the more complicated is the analytical equation and its derivation. As a general rule, analysis of combined surface- and ground-water flows by the analytical equation is not a practical approach. The mathematical model which adequately describes such flows is so complicated that the problem of deriving an analytical equation from it may seem to be more weighty than the problem of facing up to a water shortage periodically because of unenlightened management practice.

The science of hydrology has been eminently successful in providing management with relatively isolated and small bits of information indicating how various segments of the hydrologic system behave in response to change. However, each of these segments is dependent on all others, and unless all interactions are included in studies of system behavior, management operates with an incomplete concept of the system potential. Thus hydrologic data are often used very inefficiently even though every facet of the hydrologic system has been described in great detail as a separate item. One of the chief difficulties of the hydrologist striving to supply management with a truly comprehensive quantitative description of system behavior is that the simpler analytical techniques generally are ineffective, and the more complicated techniques overwhelm human capability. A change in the analytical approach is indicated as a possible means for making the hydrologist and his basic data more useful to management.

Much of the hydrologist's analysis is made from a mathematical model, as indicated earlier. The mathematical model is simply a creation of symbols and equations which in concert are supposed to behave mathematically in the same fashion as the hydrologic system behaves physically. The difficulty in using this type of model is that it must be manipulated according to prescribed rules of mathematics before an analytical equation can be obtained. The complexity of this manipulation is the immediate source of the hydrologist's trouble. Some flow problems are inherently so complicated that passage from the mathematical model to the analytical equation is not only impractical--it is impossible. Fortunately, it is unnecessary to plod along this fruitless avenue, because other types of models are far more efficient to use.

Viewing in mathematical form the laws of flow of heat, electricity, sound, and other forms of energy or matter transport, it is clearly evident that many are remarkably similar. That is, the response curves showing changes in flow have identical shapes if in each flow system the changes of flow at the boundaries and the shapes of the systems are identical. It can also be noted that the only difference among many such flow equations is the physical meaning ascribed to the symbols used and the values of constants contained in them. These identify the properties of the medium through which flow takes place and the properties of the substance or energy in transit. Thus the relative magnitudes of the constants are simply scale factors which indicate how much the response observed in one system should be shifted, amplified, or attenuated to obtain an estimate of response in another system. Recognizing, evaluating, and applying these scale factors form the complete basis for designing all types of models.

Because the laws of water flow are identical with the law defining many other types of flow, a great variety of modeling media are available to us for studying water-supply problems. Which should the hydrologist choose? The need is for a type of model which is (1) capable of automatically performing all the intricate manipulations required by the development of analytical equations, (2) relatively simple to design, construct, and operate, (3) versatile enough to produce flow predictions for a staggering variety of problems, and (4) moderately priced. Review of the possibilities for modeling the flow of water indicates that electrical models probably will be the most satisfactory. Widely published experiences with a variety of electrical model studies of open channel and pipe flow, and to a lesser extent of ground water flow, have shown their feasibility.

The analogy between flow of electricity and water is basically as shown in the following list. Each item of the electrical analog listed in the left column is proportional to the item opposite it in the right column.

Electrical-analog property	Water-system property
voltage	head
density of current flow	velocity
capacity	storage
resistance	viscous drag
inductance	momentum

One of the chief attributes of the electrical analog is the availability of ready-made components from which models may be constructed. Resistance, capacity, and inductance can be built into a model using standard parts that are mass-produced by the electronics industry and are available at low cost. Voltage and current measurements can be made in the analog using readily available laboratory and production-control instruments. Likewise, voltage and current can be controlled on the perimeter or at selected internal points of the model using commercially available regulating equipment. Thus the complete hydrologic system may be analogically duplicated by electronic components. The wide variety and excellent quality of components available bring all hydrologic problems within reach of practically useful analysis at moderate cost. Today, electrical analog devices can be constructed and observed with greater accuracy and detail than can be attained in field observation of hydrologic data.

Ground-water flow in confined aquifers is simply proportional to the ability of the aquifer to transmit water and the hydraulic gradient. Changes in head at any point in the aquifer cause a change in storage. Thus, referring to the list above, such flow through a given part of the aquifer can be simulated by resistors of fixed value which represent the viscous drag between the rock particles and water; and, the change in storage can be simulated by connecting a capacitor between the resistor net and an electrical ground. Surface water is somewhat more complicated to model because flow is not directly proportional to head gradients. For this purpose electrical components that change resistance nonlinearly with gradient or voltage may be applied. One such is the "varistor" which has much the same physical appearance as an ordinary resistor, but its resistance decreases approximately logarithmically as current flow through it increases. Another is the transistor, which can be combined with resistors to simulate the slope-stage-discharge characteristics of streams. Variable storage dependent on water stage can also be simulated by using a bank of biased diodes and capacitors, or special vacuum-tube circuits. There exists virtually an infinity of devices and combinations of devices by which the hydraulic properties of the hydrologic system can be modeled. We may say, without qualification, that any system or part of a system that is defined can be modeled electronically.

The people concerned with water in our nation have done a wonderful job of initiating and continuing a program of hydrologic-data collection. However, the analytical methods commonly used for translating basic data into predictions of response to full water development are inadequate. They do not provide water management with an adequate understanding of the consequences of man-made changes in water distribution. This is because the commonly used methods are at best capable only of describing the interrelationships between relatively few factors in the hydrologic system, and then only if these factors are of simple form and, of course, are known. It is suggested that the electric analog be used for predicting the response of the hydrologic system to proposed man-made changes. With such an analytical tool, the hydrologist can include all the pertinent hydrologic factors in his analysis. He may model the hydrologic system much more accurately than by mathematical methods, because few accurate and complete mathematical models can be analyzed successfully. The improved accuracy and comprehension of data analysis through electrical models should lead to better water management, which could lead to a more effective use of water for us all.

QUALITY OF GROUND WATER--CHANGES AND PROBLEMS

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Changes and problems associated with quality of ground water, as presented in this paper, are separated into three categories: (1) general characteristics of water; (2) changes in quality of ground water; and (3) quality-of-water problems associated with ground water.

Information on the quality of ground waters is obtained by representative sampling of various aquifers in areal or hydrologic studies of the water resources. Standard analytical methods are used to determine the chemical composition of these representative water samples. Chemical analytical results are used as an aid in determining the source of under-ground and surface waters and in defining the subsurface geology of an area.

For many years the U. S. Geological Survey and the State of New Mexico have cooperated in the study of ground-water quality in New Mexico. This paper presents general information on the quality of ground water that has been learned from these investigations and from reports of the Geological Survey and other Federal agencies.

All water is wet and, except for water containing suspended matter or organic material, it all looks about the same. Frequently, the similarity ends at this point. Distilled water and sea water may be cited as examples of the above criteria.

Water often is called the universal solvent because most substances are soluble in it, at least to a small degree. As water moves through the hydrologic cycle from rain, to surface runoff, to infiltration into the ground-water table, it dissolves gases of the atmosphere and soil and earth minerals and picks up suspended material. Even rainfall contains a certain amount of these materials. Surface runoff normally contains small to moderate amounts of dissolved solids and after heavy rains may contain a large amount of suspended matter. As the water percolates into the ground-water table, generally all of the suspended matter is removed; hence, the suspended sediment loads of natural recharge water are usually of no consequence in ground-water investigations.

The type of dissoved minerals in natural water depends primarily on the type of rocks or soils with which the water has been in contact and the length of time of contact. Ground water generally is more saline than surface runoff because it remains in contact with rocks and soils for much longer periods.

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Composition of ground water

The principal constituents of ground water are the bicarbonates, sulfates, and chlorides of the alkaline earth and the alkali metals. Other constituents often present in ground water, but usually in lesser amounts, are silica, iron, manganese, heavy metals, fluoride, nitrate, phosphate, boron, hydrogen sulfide, and carbon dioxide.

The source and the significance of some of the dissolved constituents of natural water are discussed in the following paragraphs.

Silica is dissolved from practically all rocks and usually is nonionized. Because quartz is so resistant to solution by water, most silica in water probably is derived from the decomposition or metamorphism of silicate minerals rather than from solution of quartz. Water from many sources contains less than 10 ppm (parts per million) of silica. However, water that contacts deposits high in silicate minerals, particularly the feldspars, may contain as much as 60 ppm silica. Concentrations exceeding 100 ppm of silica are rarely found in natural water (Rainwater and Thatcher, 1960, p. 259).

Iron, one of the most abundant minerals in the earth's crust, occurs in the dark-colored silicate minerals of igneous rocks, and as sulfides and oxides. Iron oxide and iron hydroxide are often present as cementing materials in sandstone. Although iron is fairly soluble, it is usually found only in small concentrations in water because it is readily precipitated as a hydroxide (Rainwater and Thatcher, 1960, p. 183). For most uses, concentrations exceeding 0.3 to 0.5 ppm are objectionable.

Calcium occurs in most rocks and soils. The highest concentrations usually found in water that has been in contact with limestone, dolomite, or gypsum. Water that has been in contact with granite generally contains less than 10 ppm of calcium, whereas water that has been in contact with dolomite or limestone may contain from 30 to 100 ppm of calcium (Rainwater and Thatcher, 1960, p. 127). Gypsum, which is abundant in New Mexico, is the greatest contributor of calcium to water. Water that has been in contact with gypsum may contain several hundred ppm of calcium.

Magnesium is dissolved primarily from dolomitic rocks. Soft water usually will contain only 1 or 2 ppm of magnesium, but water that has been in contact with dolomite may contain as much as 20 to 100 ppm (U.S. Geol. Survey WSP 1522, 1961, p. 10).

Sodium and potassium have similar characteristics and usually are found together in most soils and rocks; however, sodium is more abundant in nature than potassium. Sodium usually is the predominant cation in the highly mineralized water in the western United States. When the concentration of sodium and potassium are both low, they may be of about equal proportions; in high concentrations, sodium usually predominates. Sodium remains in solution rather persistently when it is leached from rocks, whereas potassium is easily recombined with other products of weathering such as the clay minerals (Hem, 1959, p. 89). Frequently the concentration of sodium and potassium is computed rather than determined by specific analysis and is reported as the equivalent amount of sodium. The use of sodium salts is common in industry, and many industrial wastes may contain large quantities of sodium that may find its way into streams or ground-water aquifers.

Bicarbonate and carbonate are common in ground water because of the abundance of carbonate minerals in nature and because carbon dioxide, that helps dissolve them, is readily available (Rainwater and Thatcher, 1960, p. 93). Bicarbonate concentrations range from less than 50 ppm in water from relatively insoluble rocks to as much as 400 ppm in water from limestone (U.S. Geol. Survey WSP 1522, 1961, p. 11).

Sulfate occurs in most sedimentary rocks and soils. It is especially abundant in gypsum and in some beds of shale. Water from mines may be high in sulfate as a result of the oxidation of pyrite. Organic material containing sulfur may also add to the sulfate content of water. Sulfate is discharged by many industrial plants as a waste product (Rainwater and Thatcher, 1960, p. 279). As a result, sulfate concentrations in both surface and ground waters may range from a few parts per million to several thousand parts per million.

Chloride is the major anion in many natural water supplies and in most brines. Chloride concentrations in natural water may range from less than 1 ppm in fresh water to several thousand parts per million in brines (Rainwater and Thatcher, 1960, p. 141). Irrigation return flows and industrial wastes may greatly increase the chloride content above that generally found in natural water.

Fluoride is only sparingly soluble and is present in most natural waters in only small amounts. Calcium fluoride is its principal source. The element is often characteristic of water from deep strata and is frequently found in salt water from oil wells (Rainwater and Thatcher, 1960, p. 163).

Nitrate is another anion found in a wide range of concentrations in ground water. Normally, concentrations of nitrate are low in natural water, and high concentrations of nitrate generally indicate contamination by sewage or organic material. If contamination of an aquifer by sewage or industrial waste is suspected, the nitrate concentration should be determined and checked against previous determinations if they are available. Hem (1959, p. 118) reports that contaminated water in Carlsbad Caverns had a nitrate content of about 850 ppm.

Boron is present as an anion or in nonionic form in natural water. Boron concentrations are generally quite small in comparison to other consituents, and a concentration of 5 ppm is considered very high. The element is essential to plant growth but is toxic to most plants at concentrations of more than 2 or 3 ppm. The higher concentrations of boron are usually found in water that has been in contact with igneous rocks (Rainwater and Thatcher, 1960, p. 113).

Many other constituents occur in natural water in very small, or minute quantities. The more common of these are aluminum, manganese, chromium, nickel, copper, lead, zinc, cobalt, arsenic, selenium, cadmium, strontium, phosphate, and barium. Thus, high concentrations of any of these constituents generally indicate contamination from sources such as industrial or sewage effluent, insecticides, pesticides, or herbicides. Some of these minor constituents--such as lead, arsenic, and selenium--are toxic to human beings or animals if present in high concentrations. The U. S. Public Health Service (1961, p. 11) drinking water standards states that the presence of lead or arsenic in excess of 0.05 ppm or of selenium in excess of 0.01 ppm constitute grounds for rejection of the supply.

Physical properties of natural water

Various physical properties affect the quality of water. Color, taste, odor, temperature, sediment content, and specific conductance must be given consideration when water is to be used for domestic, municipal, or industrial purposes. Color in water usually is caused by organic matter that is extracted from leaves, roots, or other organic substances in the ground. A high concentration of one or more of the inorganic constituents previously discussed often causes an objectionable taste in water. Odor may be caused by gases released from decomposition of organic matter or sewage effluent. Except for thermal springs, groundwater temperatures usually are quite uniform for a given depth below the land surface. However, these temperatures may be altered by industrial use. Ground water that is used for cooling and then is returned to the aquifer will cause a temperature change in the aquifer.

Specific conductance of water is a measure of its capacity to conduct a current of electricity. It varies with the concentration and degree of ionization of the different minerals in solution and with the temperature of the water. Specific conductance is useful in evaluating chemical quality of water. It may be used for estimating the dissolved solids in solution, as the dissolved solids in parts per million usually will equal about 65 percent of the conductance value expressed in micromhos per centimeter at 25°C. Relatively easy to determine, either in the field or in the laboratory, it is a very popular determination for estimating quality of water.

Expression of Water Analyses

The quantities of dissolved materials found in water usually are expressed in parts per million. A part per million is a unit weight of a constituent, or constituents, in a million unit weights of solution.

Chemical analyses frequently are expressed in equivalents per million. An equivalent per million is a unit chemical combining weight of a constituent in a million unit weights of solution. Water is electrically neutral. Thus for the dissolved constituents, the sum of the charges on the cations, positively charged ions, must equal the sum of the charges on the anions, negatively charged ions. The accuracy and the completeness of a chemical analysis, in which the common anions and cations and silica have been determined, can be checked.

Factors Affecting Quality of Ground Water

Water is nearly always moving and is constantly undergoing change. Two general types of phenomena--natural and artifical--affect the quality of water. The two most important natural phenomena are the precipitation pattern and the intensity of precipitation. The runoff and the recharge water from precipitation that falls on soluble rocks such as gypsum or dolomite will contain higher concentrations of dissolved solids than water from precipitation falling on relatively insoluble rocks such as igneous rocks. Intensity of precipitation also can have an affect on the quality of ground water. If the precipitation is intense and of short duration, only a small portion of the total rainfall will filter into the ground and little or none will reach the water table, and there will be little affect on the quality of the ground water. On the other hand, if the rainfall is of low intensity and long duration most of it may filter into the ground to dissolve minerals from the material through which it passes. Thus the type of soil or rock that makes up the zone of recharge and the distance between the zone of recharge and the aquifer also have major influence on the quality of the water.

Evapotranspiration is another phenomenon that affects shallow aquifers. Evapotranspiration will increase the dissolved solids in water because the water is removed and the dissolved minerals remain.

Many artificial factors can create changes in the quality of ground water. The drilling of a well and the method of casing it are important factors in the quality of water obtained from the well. Mixing of waters of different quality may take place in a well penetrating more than one aquifer.

Mixing of water from different aquifers is not always bad, but it may create problems if it is not anticipated and understood. Pumping may induce a change in the quality of the ground water even when only a single aquifer is penetrated. Intermittent pumping probably will have little effect on the quality of the water, but continued pumping creates a larger zone of depression and causes water from greater distances or other aquifers to move into the area. If this water has been in contact with other type materials, the quality of the water in a given well may change considerably. Pumping may create changes in the quality of ground water in closed basins. Wells in these areas usually are drilled in a ring around the fringe of the basin. The slope of the ground-water table normally is towards the center of the basin, and an increase in the salinity generally occurs in the same direction. Heavy pumping in the fringe area can create a water table slope in the opposite direction and permit the saline water from the central area to flow into the fresh water. Thus in closed basins water-table levels and slopes should be watched closely when heavy pumping is taking place.

Irrigation often will affect the quality of shallow-water tables in or near the irrigated area. Irrigation has a tendency to increase the dissolved-solids content of the soil water because crops use water almost always in excess of the salt intake and leave the increased concentration of salts in the soil.

These salts may be leached out by excessive use of irrigation water or by rain. The excess salts gradually will filter into the shallow-water table by direct percolation or by flowing into streams and returning to the water table at some downstream point.

Industrial and municipal wastes are sources of artifical change in the quality of ground water. When waste effluents are discharged into a stream the water may get into a ground-water table at some downstream point. A relatively new factor in this type of waste is detergent material. Synthetic detergents are materials that have the cleansing action of soap but are not derived directly from fats and oils. They are not readily removed from sewage by normal treatment. In many rapidly growing areas such as near Albuquerque and other large cities in the state, sewage is kept in cess pools or septic tanks. When this situation exists, detergents may find their way directly into the ground water.

Artifical recharge may affect the quality of ground water. Artifical recharge has not been used extensively before the present time, but considerable study has been made of it as a means of storing water for future use. Generally, the chemical quality of the water changes if water from the surface is injected directly into a ground-water aquifer. This change may range anywhere from a slight concentration of dissolved solids to a change that causes precipitates to form in the aquifer. Suspended sediment is another factor that may change the quality of ground water if it is injected with the artifical recharge water. As most surface water contains suspended sediment, this material should be removed before the water is injected into the aquifer; otherwise, the pores in the aquifer may become clogged. Also, an exchange between ions of sediment and ions in solution may take place and create a change in the quality of the water.

Quality-of-Water Problems Associated with Ground Water, General

Dissolved minerals usually limit the suitability of water for certain uses. Quality-of-water problems usually are intensified in ground water because ground water frequently is more saline than surface water. Quality-of-water problems and water utilization are intricately related. Some constituent that may create a problem for one type of use may actually be an asset for another use. For example, nitrate is objectionable in concentrations of as much as 45 ppm in domestic or municipal water supplies, but it usually is an asset for irrigation purposes.

The most common quality-of-water problems associated with ground water will be discussed as various problem types. All of us, regardless of our profession or professional connection with water problems, are concerned primarily with domestic and municipal supplies, because each and every one of us has a personal interest in how these supplies may affect our day-to-day activities. Therefore, let us consider the effect that some of these major constituents have on our domestic and municipal water supplies. Silica is not physiologically significant to humans or livestock, (Rainwater and Thatcher, 1960, p. 259) but it creates a quality-of-water problem because it contributes to the formation of scale in plumbing fixtures. Calcium and magnesium cause hardness in water. The higher the concentration of these constituents, the greater the hardness and the more soap that will be required for laundering. Tolerance for hardness is a relative factor. Water that might be considered soft in New Mexico or in the Southwest probably would be considered hard in the eastern part of the United States. However, regardless of the locality, water containing more than approximately 200 to 300 ppm hardness would be considered hard. The national average hardness for domestic water supplies is about 100 ppm (Lohr and Love, 1954, p. 19). It might be of interest to compare the hardness of the municipal supplies of the major cities in New Mexico to the national average. The U. S. Geological Survey Water-Supply Papers 1299 and 1300 entitled "The Industrial Utility of Public Water Supplies in the United States, 1952" present representative chemical analyses and miscellaneous information such as ownership, source, treatment and storage facilities concerning the water supplies of the major cities of the United States.

Water-Supply Paper 1299 is for the states east of the Mississippi River, and 1300 is for the states west of the Mississippi River. Water-Supply Paper 1300 lists 13 cities in New Mexico which were major cities on the basis of the 1950 population. Of these 13 cities, 10 obtained their water from ground-water sources, two from surface-water sources, and one from a mixture of surface and ground-water sources. Hardness of water of the two cities using surface-water sources was less than the national average of 100 ppm. One city obtaining its water from a ground-water source was at the national average of 100 ppm. Four cities using ground water, and one using surface water had water hardness ranging from 100 to 200 ppm hardness. There were two cities using ground water sources with 200 to 300 ppm hardness, two cities using ground water had 300 to 500 ppm hardness, and four New Mexico cities using ground water had hardness concentrations in excess of 500 ppm. No specific cities that fall in the various categories were named; however, the above figures were taken from Water-Supply Paper 1300 (Lohr and Love, 1954, p. 286-296).

Sodium and potassium are not particularly objectionable in municipal or domestic supplies, but they will contribute to the saltiness of the water. Sulfate combined with calcium will tend to form hard scale in pipes. If large amounts of sulfate and either magnesium or sodium are present, the water will have an adverse biological effect upon a person, as the chemical constituents of epsom salts and glauber's salts are magnesium-sulfate and sodium-sulfate respectively. Chloride contributes to the saltiness of the water supply and may cause the water to be corrosive if the water contains large quantities of calcium or magnesium (U. S. Geol. Survey WSP 1522, 1961, p. 11).

Fluoride in water has been a rather controversial issue in some municipalities in recent years. Studies indicate that the incidence of dental decay is less in areas having water supplies containing a small amount of fluoride than when there is none. However, concentrations greater than about 1.5 ppm may cause mottled teeth in children during calcification or formation of the teeth (Dean, 1936, p. 1269-1272). According to the National Research Council, Maxcy (1950, p. 271) concludes that nitrate concentrations in excess of about 44 ppm may contribute to the occurrence of blue babies and should be regarded as unsafe for infant feeding.

The U. S. Public Health Service (1961, p. 11) drinking water standards recommend that dissolved solids should not exceed 500 ppm. According to Water-Supply Paper 1300, three of the 13 cities listed in New Mexico have water supplies with dissolved-solids contents of less than 200 ppm. All three of these supplies are surface water. Six New Mexico cities use ground-water sources in which the dissolved-solids content ranges from 200 to 500 ppm. Five cities in the State use ground-water sources that have water supplies with 500 to 1000 ppm. Three cities use ground-water supplies that contain more than 1000 ppm. Fortunately, these three cities have other sources of water. One has a source in the 200 to 500 ppm range, and the other two have sources in the 500 to 1000 ppm range.

In addition to setting a maximum recommended dissolved-solids content for drinking water, the U. S. Public Health Service states that the following chemical constituents in water supplies should not exceed the concentrations shown in parts per million (U.S. Public Health Service, 1961).

Substance	Concentration in mg/l
Alkyl Benzene Sulfonate (ABS)	0.5
Arsenic (As)	.01
Chloride (Cl)	250
Copper (Cu)	1.0
Carbon Chloroform Extract (CCE)	.2
Cyanide (CN)	.01
Fluoride (F)	1.5
Iron (Fe)	.3
Manganese (Mn)	.05
Nitrate (NO_3)	45
Phenols	.001
Sulfate (SO_4)	250
Total Dissoved Solids	500
Zinc (Zn)	5.0

The greatest use of water in New Mexico is for irrigation. The U. S. Department of Agriculture recommends that the conductance of water used for irrigation should not exceed 2,250 micromhos per centimeter unless the water is used abundantly and subsoil drainage is good (U.S. Salinity Laboratory Staff, 1954, p. 70). In New Mexico, ground water containing several thousand parts per million dissolved solids sometimes is used successfully for irrigation where the land is well drained and the soluble salts can be removed through the application of large volumes of water. This practice is used most extensively in the lower Pecos River valley. A saline condition will gradually develop in the soil, and an alkali flat that will not support vegetation will eventually develop if water having a high content is used for irrigation where drainage is not adequate.

High sodium concentrations in irrigation water may create soil problems. In evaluating water to be used for irrigation, sodium is expressed as percent sodium, which is the ratio of sodium to the sum of all cations multiplied by 100 on the basis of concentrations expressed in equivalents per million. A percent sodium inexcess of 60 is generally considered undesirable for irrigation water because it will have a tendency to make the soil impermeable to water.

Another factor of water quality that must be considered in irrigation is residual sodium carbonate. If the irrigation water contains a high concentration of the bicarbonate ion, calcium and magnesium carbonate tend to precipitate out of the solution. If this occurs, the concentrations of calcium and magnesium in the solution are reduced, and the relative proportion of sodium is increased. The bicarbonate that remains in solution after the calcium and magnesium have precipitated will combine with sodium to form residual sodium carbonate. Increasing the percent sodium has the same effect as that previously described for sodium, and the sodium carbonate tends to produce the condition known as black alkali. Irrigation water containing more than about 2.5 epm (equivalents per million) of residual sodium carbonate generally is considered unsuitable for irrigation. However, if the land is well drained and the soil is sandy, it is often possible to irrigate with water containing much more than the recommended 2.5 epm of residual sodium carbonate (U. S. Salinity Laboratory Staff, 1954, p. 81-82).

Sodium chloride, the most common salt in saline water, also influences the suitability of ground water for irrigation use. Very few useful plants can tolerate a high concentration of sodium chloride.

Boron is another constituent in water that may limit the suitability of water for irrigation. Boron in very small quantities is essential to plant growth, but it is very toxic at concentrations only slightly more than the optimum. According to the U. S. Department of Agriculture, boron sensitive crops such as oranges, apples, or navy beans can stand about 1 ppm of boron; and boron tolerant crops such as cabbage, alfalfa and sugar beets can tolerate about 2 or 3 ppm of boron (U. S. Salinity Laboratory Staff, 1954, p. 67, 81).

Quality of water causes various problems for industry. As more and more water in the state is diverted to industrial use, these problems will probably be magnified. Quality-of-water problems associated with industry are usually quite different from those associated with irrigation. For example, quality of the water frequently dictates the type of crop that may be grown with irrigation or the type of soil and drainage that are necessary. On the other hand, industry is usually able to seek out the quality of water that it needs or can alter it to fit its needs because of the smaller amount of water used and the higher unit economic value of the product produced. Industries generally will not locate in municipalities having water of poor quality. In general, each industry has its specific water requirements and is usually prepared to alter the water to fit its particular needs (California State Water Pollution Control Board, 1952, p. 127). Ground water is often used by industry because it is generally of a uniform quality. Ordinarily industry can treat water to fit its needs, but the treatment is simplified if the source is of uniform quality. The treatment processes of surface water used for industry must be changed when there are rapid changes in the quality of surface runoff. Most quality-of-water problems associated with industry are similar to those that were outlined for domestic and municipal use. The factors that cause scale or corrosion in plumbing fixtures will do the same thing in industrial plants. However, the problems may be more serious because of the use of high pressure boilers in many industries.

Quality-of-Water Problem Areas in New Mexico

Before closing I would like to discuss briefly the quality of water and a few of its allied problems in specific areas in the State of New Mexico. The chemical quality of ground water in New Mexico is variable. Analyses of two water samples collected in two different areas of New Mexico support this statement. For example, water from a spring in the Sangre de Cristo mountains in northern New Mexico has a dissolved-solids content of only 21 ppm. The opposite extreme is represented by a brine sample that has a dissolved-solids content of 275,000 ppm. The source of this sample is a test well in the Malaga Bend area in Eddy County in southeastern New Mexico. The average concentration of sea water is about 35,000 ppm; thus, this brine has roughly eight times the dissolved-solids content of sea water.

There are relatively few quality-of-water problems associated with ground water in the high mountain country of New Mexico. Most of these problems are in the lowlands or river valleys where irrigation is practiced extensively and the ground-water reservoir is often recharged from the streams.

Above Elephant Butte Reservoir, the Rio Grande basin has relatively few quality-of-ground-water problems. However, downstream in the Mesilla Valley, deterioration of quality of ground water is recognized. The deterioration probably is caused by two factors: (1) recharge from the Rio Grande, which has a greater dissolved-solids content downstream than above the Reservoir and (2) extensive pumping that has been done in past years to augment the surface-water supply. Pumping has brought ground-water from greater distances than is ordinary and, as might be expected, dissolved-solids content of the ground water has increased.

Quality-of-water is a much greater problem in the Tularosa "closed basin." Except for a fringe around the edge of the basin, most of the ground water in the Tularosa basin is saline and cannot be utilized. Thus, it is difficult to find potable-water supplies for the expanding population and the military facilities in the basin.

The upper Pecos River valley, as in the upper Rio Grande basin, does not have any particular quality-of-water problem. However, many of the ground-water supplies in the middle Pecos River valley have very high concentrations of calcium and sulfate because of solution of underground gypsum deposits. In general, the water in the middle valley is suitable for irrigation, but in many places it is unsuitable for domestic or municipal supplies. As in the Mesilla Valley, the quality of the ground water has deteriorated because of heavy pumping and the resultant import of water. Another factor that contributes to deterioration of the quality of ground water in shallow aquifers of the middle Pecos valley is phreatophytes, principally salt cedar. Salt cedars have a tendency to increase the concentration of the dissolved solids in the shallow aquifers because they use the water and leave most of the salts behind.

The quality-of-water problems in the lower Pecos River valley are of the same type as those in the middle valley, but they are magnified. Some of the ground water in the lower basin is brine that originates from ground water flowing through and over evaporite deposits. These deposits are predominantly sodium chloride, or common table salt. However, some of the brines are also quite high in calcium, magnesium, and sulfate. Some of the ground water used in the lower Pecos valley for irrigation has considerably higher dissolved-solids content than that recommended by the U. S. Department of Agriculture. Thus, excess water must be used and adequate drainage must be provided to insure continued production.

Quality-of-water problems have an entirely different pattern in the high plains of eastern New Mexico. As there is very little surface recharge to the ground-water table in this area, irrigation practices do not have as great an affect on the quality of the water as they do in some of the river valleys. Probably the greatest quality of water problem in the high plains area is contamination of some aquifers by oil-field brines. Also, in the high plains there are areas where nitrate concentrations exceed 40 ppm and fluoride concentrations range from 5 to 7 ppm.

The San Juan basin also has quality-of-water problems. In general, the shallow water tables along the San Juan river contain good water where they are recharged from the river. However, the ground water in deep aquifers is brackish or saline in many places. Also, in the San Juan basin heavy pumping has had its effect on the quality of the ground water as ground water from other areas has been imported.

High nitrate concentrations occurring in ground-water aquifers, as a result of contamination from effluent of uranium processing plants, has created a quality-of-water problem in some areas of the state. However, this situation is probably under control at the present time because of changes in processing methods.

The quality of ground water problems that I have just discussed in the various areas in the state are general in nature and, in most cases, are the predominant ones. I doubt if there is any quality of water problem that is restricted to any one specific area.

Conclusion

Many of the quality-of-water problems are natural phenomena, but the majority of them are caused, or are complicated, by man's activities. Any use man makes of water, whether it be domestic, municipal, irrigation, or industrial, will affect the quality of the water. Because of limited water supplies and increased demand for water, research in quality of water and in man's activities with water is needed to determine what can be done to minimize these changes.

References

California State Water Pollution Control Board, 1952, Water quality criteria: Pub. No. 3.

Dean, H. T., 1936, Chronic endemic dental fluorosis: Am. Med. Assoc. Jour., v 107, p. 1269-1272.

Hem, J. D., 1959, Study and Interpretation of the Chemical Characteristics of Natural Water: U.S. Geol. Survey Water-Supply Paper 1473.

Lohr, E. W., and Love, S. K., 1954, The Industrial Utility of Public Water Supplies in the United States, 1952: U.S. Geol. Survey Water-Supply Paper 1300.

Maxcy, K. F., 1950, Report on the relation of nitrate concentrations in well water to the occurence of methamoglobinemia: Natl. Research Council, Bull, Sanitary Eng. and Environment, p. 271, app. D.

Rainwater, F. H., and Thatcher, L. L., 1960, Methods for Collection and Analysis of Water Samples: U.S. Geol. Survey Water-Supply Paper 1454.

U. S. Geological Survey, 1961, Quality of Surface Waters of the United States, 1957, Parts 7 and 8, Water-Supply Paper 1522.

U. S. Public Health Service, 1961, Report of the Advisory Committee on Revision of the Public Health Service 1946 Drinking Water Standards: Am. Water Works Assoc. Jour. v. 53, No. 8, p. 935-945.

U. S. Salinity Laboratory Staff, 1954, Diagnosis and Improvement of Saline and Alkali Soils: U.S. Department of Agriculture Handbook No. 60.

GROUND WATER AND GROUND WATER LAW IN NEW MEXICO

Governor Edwin L. Mechem[1/]

In 1950, in a report entitled Water Resources Law the President's Water Resources Policy Commission observed that "New Mexico, while not the first state to enact ground-water legislation, has pioneered in this field, in that its ground-water legislation...was the first of the ground-water statutes to be put into action and has set the pattern for much of the subsequent legislation in that field."

Now, first is not necessarily best. But the basic New Mexico statute has proved serviceable, even though it was adopted at a time when many of the problems that challenge us today had not been recognized. Administered from the beginning by officials whom Robert Emmet Clark describes as "imaginative, inquiring, and conscientious beyond what can usually be expected of modestly paid civil servants," and constructively interpreted from time to time by enlightened courts, the law has met the test of adequacy.

How did enactment of this pioneer instrument come about, more than 30 years ago? The story is too long to be told in detail here this evening. But we can hit a few of the high places.

Laws are shaped by need. And when it is considered that white settlement of this land of little rain began some 350 years ago, one might wonder that regulation of the use of ground water did not come much earlier. The truth is that in New Mexico intensive development of ground water, calling for statutory control of appropriation and development, occurred only in relatively recent times.

Although there was early development, thirteen prehistoric shaft-like excavations which seem to have been aboriginal wells several thousand years old have been excavated at the well-known "early man" site near Portales. The site is an abandoned gravel quarry near the western edge of the southern High Plains, on the bed of an ancient lake.

The conical shafts are about 6 feet deep and about 2 feet in diameter at the bottom. Excavated materials indicate that water stood in all 13 pits, and that all 13 were refilled with earth shortly after being opened.

Archaeologists speculate that many more such wells were opened here by paleo-Indian transients who used the site as a way-station. They speculate further that the wells were refilled at the end of each encampment to protect the water against contamination or drying up, and possibly to keep its presence a secret from other transients.

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It would seem, then, that New Mexicians have been concerned with developing and conserving ground water supply and forestalling junior appropriators since about the tenth or eleventh century, B.C. Perhaps it could have been expected that we would be among the first to come up with solutions.

A prehistoric well similar in structure but somewhat deeper than the High Plains well was excavated recently on the opposite side of the State among paleo-Indian ruins in the Gila wilderness -- redemonstrating that New Mexicans have long known where to look for water when the surface supply runs short.

For the most part, the sedentary agricultural Indians who lived and farmed in New Mexico at the time of the Spanish entrada established their communities near springs and perennial streams, and depended upon surface flows for domestic and agricultural uses; though when surface flows were unavailable those people also opened shallow wells in dry lake and river beds to reach underground water. There are definite records of this practice in Gran Quivira (in 1661) and at Zuni and Pecos pueblos (in 1776), and it can be presumed to have dated back to pre-Columbian times.

The chronicles of Coronado record that inhabitants of Moho Pueblo north of present Bernalillo attempted to dig a well within the pueblo walls while resisting a siege by Spanish soldiers in 1541, but failed to reach water and were forced to surrender in consequence.

The first Spanish colonists depended principally on surface water to supply their needs, and the example of the Mohos seems not to have impressed them, for they apparently did not provide even their places of fortification with wells. Paul Horgan in Great River mentions a well in the garden of the Palace of the Governors in Santa Fe in the 1670's, but it apparently was not in operation in 1680, the year of the great pueblo rebellion, for the Indian besiegers diverted the flow of the palace ditch to force the Spanish capitulation, and also that De Vargas used the same strategy in reconquering the capital from the Indians in 1692.

Ralph Twitchell's book Old Santa Fe describes another well in the palace patio in 1716. This well may have been constructed to offset a decline in surface supplies, and it is likely that other wells were opened in the same general period--particularly as settlement moved southward from the northern mountains. A dug well still in existence near Pecos village is said to date back to Spanish or Mexican times, but records on it are lacking.

It is generally agreed, however, that the water well had no prominent place in the Spanish scheme of colonization.

After the occupation of New Mexico by the United States in 1846, the development of ground water for drinking purposes was accelerated. By 1850, Topographical Engineers of the United

States Army were prospecting in the so-called "Great American Desert" for what then was called "earth water" or "phreatic water" for use along the stage and freight roads -- and, ultimately, to determine routes along which railroads would be built through the arid Southwest. These explorations produced flowing artesian wells in some areas, and there was interest in developing them for irrigation at surprisingly early dates.

The historian Bancroft records that in the 1850's "The boring of artesian wells for an increased water supply was often urged and sometimes discussed in government reports. In 1858-59, a well was bored near Galisteo to a depth of 1,300 feet, but though it showed the practicality of wells for travelers it did not bring the water to the surface, and so far as irrigating was concerned it was considered a failure." And the heartbreaking efforts of Captain John Pope of the Topographical Engineers to find flowing artesian water in the vicinity of what is now known as Pope's Crossing of the Pecos River near the New Mexico-Texas line from 1855 to 1858 are described in a recent issue of New Mexico Magazine.

Had the Captain bored his exploratory deep wells some 50 or 60 miles to the north, his reputation would have been enhanced, and the development of the Roswell artesian basin would have come about some 50 years before it did.

From their earliest penetration of the western arid zones, the railroads had used windmills to raise ground water for their locomotives -- huge structures with fans sometimes 30 feet in diameter. By the middle 1870's, a smaller windmill for ranch and homestead use had been engineered, and its mass production revolutionized the western livestock industry and the pattern of settlement in general. Then as now, however, wind-powered pumps could not lift water in quantities sufficient for field irrigation, and except where flowing artesian water was discovered successful application of well water to irrigation awaited perfection of the centrifugal pump.

In 1891, while sinking a well to serve his household needs, Nathan Jaffa, a prominent citizen of Roswell, brought in a flow of artesian water, and there followed a bonanza in ground-water development which ultimately involved large portions of Chaves and Eddy counties. By 1910, the Roswell flats supported the richest farming community in New Mexico. Development and use of surface water had been brought under control of the state by the water code of 1905, but there was no control of the appropriation of ground water. In the Roswell artesian basin, any farmer who could afford to construct a well could develop a private water supply, without the expense of pumping or of joining with his neighbors to finance construction of costly surface-water storage and distribution works.

In the meantime, the phenomenon had attracted the attention of the United States Geological Survey, and shortly after 1900 Mr. C. A. Fisher of that agency began a study of the geology and hydrology of the entire artesian basin. Results of the study were published as Water-Supply Paper 158 of the Survey. Utilizing the study's findings, and urged on by the Roswell water users, the legislature in 1905 adopted "an act to regulate the use of artesian wells and to prevent the waste of subterranean flows of water."

The date 1905 is significant in the history of water legislation in New Mexico. This was the year of enactment of the first New Mexico statute regulating appropriation of surface water. This statute, rewritten in 1907, first declared the surface waters to be public and subject to appropriation.

The 1905 artesian water law did not mention public ownership or prior appropriation. It declared any artesian well "not tightly and securely cased, capped, or furnished with such mechanical appliances as will readily and effectively arrest and prevent the flow of water from the well" to be a public nuisance, the owner guilty of a misdemeanor. It authorized the governor to create "artesian districts" and to appoint "artesian well supervisors" to enforce terms of the act. It anticipated the doctrine of prior appropriation by requiring all well owners to register their wells with the supervisor, recording such information as location, date of construction, capacity, and use of flow. All persons drilling new wells were required to notify the supervisor in writing of the location of the well and the type of casing planned.

The supervisor could condemn any well whose casing was deemed faulty or inadequate.

Governors apparently did not respond to their new powers in a manner acceptable to the Roswell irrigators, for we find the legislature in 1909 taking the power to create "artesian districts" away from the chief executive and authorizing county commissioners to create "County Artesian Well Boards," which were empowered in turn to appoint artesian-well supervisors and in general to oversee uses of artesian water. It limited the distance which artesian water could be transported from wells in lined and unlined ditches, and specified a maximum allowable use in irrigation at 3 acre-feet per acre per year. It authorized the well supervisor to make inspection of works, to measure flows of wells, to shut down wells which violated any provision of the act.

The statute applied only to artesian water and, therefore, was operative only in certain areas in Chaves and Eddy counties. And I'm sure that our guests from Colorado and Texas will indulge me in the observation that -- as regards control of the appropriation and use of ground water -- the Territory of New Mexico in 1909 stood just about where their states stand today.

Coming back to the Roswell Flats, exploration widened to more than 660 square miles the area upon which flowing wells could be obtained, and optimism ran high. In 1912, the legislature redefined artesian wells to include all wells "finished in artesian strata whose waters may or may not flow to the surface under natural pressure," and imposed further safeguards against waste.

But new development continued to go in, and by 1915 it was apparent that artesian pressures were declining.

By the early 1920's wells in almost a third of the originial artesian area had ceased to flow. At this time the efficieny of pumping equipment had been greatly improved, and in most instances when a flowing well failed the owner merely installed a pump and went on irrigating as before.

By 1925, more than 1,400 artesian wells were in operation in the Roswell basin, irrigating something like 45,000 acres. But the bonanza had burned itself out. Water levels continued to decline and more wells failed. Banks refused to invest more money in irrigated farms until some means of protecting investments could be devised.

The situation affected and concerned the entire community, and in 1925 the Roswell Chamber of Commerce urged the legislature to appropriate money to finance an investigation of conditions in search of a remedy. The legislature appropriated $5,000 to the State Engineer to initiate the study. Under an ensuing agreement, the U.S. Geological Survey allotted an equal amount for the study. Subsequently, the State and the Survey each contributed an additional $4,500 and Chaves and Eddy counties subscribed lesser amounts.

The investigation was carried out by A. G. Fiedler, B. C. Renick and S. S. Nye of the Geological Survey. The findings were just about what most irrigators had suspected. Pressures were declining because a limited supply of artesian water was being over-developed. The study recommended that controls be instituted immediately, and Mr. Fiedler worked closely with local water users and attorneys in framing a statute which would apply the doctrine of prior appropriation to ground water. So, once again the Roswell irrigators took up the cudgels for conservation of an invaluable resource -- joined now by irrigators in Lea and Luna counties, where pump-irrigation from shallow wells was getting under way.

And, once again, the legislators of New Mexico reacted in a responsible and enlightened fashion. The surface-water code of 1905 and 1907, based on the doctrine of prior appropriation, had met and passed the test of time. In an historic action in March 1927, the legislature empowered the State Engineer to control ground water development and use under the appropriative doctrine, throughout the State.

The 1927 ground-water statute contained only six sections and somewhat less than 400 words. It provided, among other things, that "All waters in the State found in underground streams, channels, artesian basins, reservoirs, or lakes, the boundaries of which may be reasonably ascertained by scientific investigations of surface indications, are hereby declared to be public waters and to belong to the public, and (to be) subject to appropriation for beneficial uses under the existing laws of this State relating to appropriation and beneficial use of waters from surface streams."

The 1927 law was almost immediately put to court test in the case Yeo versus Tweedy, eventually heard in the New Mexico Supreme Court. The statute was declared invalid because it violated Article 4 of the State Constitution, in that it attempted to extend existing legislation by reference and was, in effect, "blind legislation." However, the court stated that the statute, while objectionable in form, was merely enunciatory of existing law, was not subversive of vested rights of owners of land overlying ground waters, and was fundamentally sound. In 1931, the statute was reenacted in a form the court oulined in its opinion.

Generally, the ground-water law of 1931 is modeled after the surface-water statute of 1907. Like the 1927 ground water law, it accepts the doctrine of prior appropriation, and thus no dual doctrine of riparian and appropriative water rights emerged in New Mexico, as in some western states, to further complicate already complex problems of water administration.

For nearly 20 years, the constitutionality of the second statute was taken for granted, probably because of the declaration of the court in Yeo versus Tweedy. Then, in 1949, the validity of the entire ground-water code was challenged in the well-known case, State ex rel. Bliss versus Dority, which rose out of action by the State Engineer in enjoining unlawful uses of ground water in the declared Roswell Artesian Basin.

The defendants in the action claimed that they had acquired title to their land through United States patents which did not reserve the water and that they were the owners of the underlying waters, on common law principles. They alleged that, in violation of the State Constitution, the statute permitted the State to deprive persons of their property without due process of law and authorized the taking of private property for public use without just compensation.

In 1950, the New Mexico Supreme Court held that the Desert Land Act of 1877 had reserved underground waters for disposition according to the laws and court procedures of the various states. The defendants appealed to the Supreme Court of the United States. That Court dismissed the appeal for want of a Federal question and consitutionality of the New Mexico ground water law has not been questioned since.

Over the years, as the value of lands and crops increased, as new areas of ground-water occurrence were discovered, and as the efficiency of pumps improved, the State Engineer has found it necessary to "declare" 18 areas of ground-water control to prevent impairment of existing rights, to insure beneficial use of water, and to provide for orderly development of ground-water resources. These areas aggregate almost one-fifth of the State's total acreage. In 1960, a total of 945,000 acres were irrigated in New Mexico, of which 468,000 acres were irrigated with ground water exclusively, and an additional 150,000 irrigated acres received ground water to supplement surface-water.

Also in 1960, about 90 percent of New Mexico's industrial and municipal uses were served with ground water.

An impressive aspect of the New Mexico ground-water code is the fact that the initiative in the enactment of practically every statute originated with the users of the water themselves. This reflects an enlightened populace -- a heritage of a people's long experience in an arid environment where water is without doubt the most precious natural resource of all.

At this point, we might ask the question "Why have a ground-water law?" Why did the people of New Mexico push for its enactment, and why is there continuing vigilance against efforts to erode it?

The answers are both simple and complex. In a climate such as we have, where water demands greatly exceed supply, the use of water must be regulated, and the only practical method of regulation is through the doctrine of prior appropriation.

In arid regions such as this one, firm water supplies usually become available only through development. More often than not, the processes of development are costly and large investments are based on the water rights acquired.

Those who develop must have assurance that their investment will be protected. Under the common-law doctrine of riparian right, it is virtually impossible to establish firm water rights in arid areas, and in this day of increasing industrialization of our economy the importance of assured water supplies can scarcely be over-stated.

Perhaps this importance can best be illustrated by looking briefly at conditions in some of our neighbor states which have no effective regulation of ground water.

In 1956, the Denver Post cautioned citizens of Colorado that practically all ground water in that state was tributary to streams and therefore was subject to appropriation through surface rights. "About all it would take to shut off our wells is a lawsuit by surface-water users," the paper warned. The reporter noted that the city of Denver was underlain by a vast ground-water reservoir, but that there was no procedure in law whereby the city or any industry could establish firm rights to use of any of the water. He pointed out that a similar situation existed in the city of Pueblo, where absence of effective ground-water laws had cost the community a multimillion-dollar industrial development, auxiliary to the Colorado Fuel and Iron Company steel mills. He observed that no other steel mill in the nation had so little allied industry around it as the CF&I plant in Pueblo, and that the mills themselves divert from the Arkansas River as far upstream as Leadville, some 150 miles away. He quoted a company official as saying, "We wouldn't give any thought to underground water development. We don't use any of it. It's illegal."

In 1957, perhaps in response to sentiment stirred by the Post crusade, Colorado did enact a law intended to curtail development of ground water in the state; but the statute thus far has not proved effective, and the newspaper's comments probably would be as appropriate today as when written.

Colorado does not, of course, stand alone in her misfortune. In the Salt River Valley of Arizona, water levels in areas of intensive ground-water development have declined more than 200 feet in less than 2 decades.

In Deer Valley north of Phoenix, water levels have declined as much as 100 feet since 1954. And in the Maricopa-Stanfield area, water levels are 200 feet below their original static level -- owing principally to development which has occurred since World War II. So, it doesn't take a seventh son of a seventh son to perceive that Arizona is faced with water problems of staggering magnitude -- however favorably she may fare in ultimate division of the waters of the Colorado River.

Texas likewise is facing a day of reckoning where her ground water resources are concerned -- owing again to absence of effective state control. Water levels are declining at an alarming rate. Excessive pumping must eventually have adverse effects, and Texas cannot avoid damage to her citizens from uncontrolled use of ground waters. This truth finds illustration in what might be called the "parable of the Fort Stockton springs."

Irrigation from springs near the frontier U.S. Army outpost in the lower Pecos Valley began in the 1860's. In 1942, the year of the Pecos River Joint Investigation, some 10,000 acres were under cultivation, supporting a sound economy. Shortly thereafter the presence of a vast underground-water basin was detected north and west of the developed area, and another bonanza in ground-water development followed. By 1960, some 150,000 acres were under irrigation with ground water from artesian and shallow sources in Reeves and Pecos counties, but in the Fort Stockton area springs had ceased to flow.

Water rights dating back almost a hundred years were not being served; farmers were ruined and had no recourse under Texas law. I might add that the same thing could happen almost anywhere in Texas with no remedy in sight.

Then there is our friend California, where most rights to ground water are under a variant of the common-law doctrine. As we all know, California is now embarking on a 1.7 billion-dollar program of developing its surface waters for more efficient use, and officials have suddenly realized that effective statewide control of ground water is necessary before the plan can succeed. Only last month, the California Water Rights Board declared "It is inconceivable to us how the projects of the State water plan can operate without legislation for ground-water control." Thus in another state, the handwriting is on the wall.

In all, ground-water statutes definitely invoking the doctrine of prior appropriation have been enacted in 10 western states: Idaho, Kansas, Nevada, Oklahoma, Oregon, South Dakota, Utah, Washington, Wyoming, and, of course, New Mexico. I predict that the list soon will become much longer.

While we in New Mexico appear to have occupied the role of leadership in ground-water legislation, this is not to say that we can sit idly by -- resting on the imaginative thinking and legislating of farsighted predecessors.

If we are to grow and make the best use of our water, we must continue to bring the same imagination and scholarship to current problems in water law, and in water conservation and development. With the water users aggressively participating as they have in the past we will be more and more economical in our uses of water and will revise our water code as may be necessary for the continued growth of our economy without detriment to the rights of others and within the framework of the appropriative caveat -- first in time first in right.

AN OUTLINE OF THE STATUES GOVERNING THE APPROPRIATION AND USE OF GROUND WATER IN NEW MEXICO

S. E. Reynolds[1/]

New Mexico's ground-water code which was enacted in essentially its present form in 1931 is based on the appropriation doctrine of water rights. This is the same doctrine followed by custom, and then by law, in regard to the appropriation of surface waters in New Mexico long before statehood. Under the appropriation doctrine one has no right to the use of water simply because it flows by, or through or under his land. Under this doctrine the right first established must be first served. It seems clear that this is a very practical system for the management of water in an arid land. Certainly, development of any nature would be discouraged if it were possible for the latecomer to interfere in any way with the water supply upon which earlier investments were based.

The New Mexico statutes provide that all of the underground waters of the state belong to the public and are subject to appropriation for beneficial use. Beneficial use is the basis, the measure and the limit to the right to the use of these waters.

When the State Engineer determines that underground streams, channels, artesian basins, reservoirs or lakes have reasonably ascertainable boundaries, and he so proclaims, he assumes jurisdiction over the drilling of wells for the appropriation of ground water in such declared basins. The State Engineer has declared 19 such areas to prevent the impairment of existing rights to the use of ground water, to insure beneficial use of the water, and to provide for the orderly development of the underground-water resources of the state.

Almost one-fifth of the state's total acreage is now included within ground water basins declared by the State Engineer.

Within declared underground-water basins no well may be drilled except by a driller licensed by the State Engineer, and no well may be drilled without a permit from the State Engineer. A person not licensed by the State Engineer may construct a driven well within a declared underground-water basin provided that the casing of the well does not exceed 2-3/8 inches outside diameter. However, a permit to construct such a well must be obtained from the State Engineer.

In areas not included in underground-water basins declared by the State Engineer the underground waters still belong to the public but wells to appropriate such waters can be drilled by a person not licensed by the State Engineer and without a permit.

1/ State Engineer, State of New Mexico, Santa Fe, New Mexico.

A person seeking to appropriate the underground waters in a declared basin must make application to the State Engineer. The application must set forth the basin from which the water is to be appropriated, the beneficial use to which it is proposed to apply the water, the location of the well, the amount of water applied for, the owner of the land upon which the well is to be drilled, and, if the water is to be used for irrigation, the name of the owner of the land to be irrigated. Notice of the application must be published in a newspaper of general circulation in the county where the well will be located, at least once a week for three consecutive weeks. Objections to the granting of the permit may be filed within ten days after the last publication.

If there is no protest to granting the permit the State Engineer shall grant it if he finds that there are unappropiated waters in the designated source, and that the proposed appropriation would not impair existing water rights from such source.

If the application is protested by persons believing that their water rights would be impaired, there must be a hearing before the State Engineer. In this hearing the applicant bears the burden of proving that there is unappropriated water in the designated source and that the proposed appropriation would not impair existing rights from the source.

If the State Engineer finds after considering the evidence presented at the hearing that there is unappropriated water in the designated source and that no impairment of existing rights from the source would result, he grants the permit. If either the applicant or the protestant is aggrieved by the decision of the State Engineer he may, within 30 days, appeal to the District Court. The decision of the District Court may, of course, be appealed to the Supreme Court of the State of New Mexico.

The statutes provide that the State Engineer <u>shall</u> grant permits for the use of water for watering livestock, for the irrigation of not to exceed one acre of noncommercial trees, lawn or garden, or for household or other domestic use. Such applications are not subject to the provisions for publication of notice, protest and hearing described above.

The statutes provide that water rights for irrigation purposes are appurtenant to the land and can be severed therefrom only with the permission of the land owner.

The point of diversion of a ground-water right and the place and purpose of use of such rights may be changed upon application to the State Engineer, if the State Engineer finds that existing rights are not impaired by such changes. Applications to change the point of diversion, or place, or purpose of use, are subject to the same provisions for publication of notice, protest and hearing which relate to applications to make a new appropriation.

A permit ripens into a license to appropriate when the water has been applied to beneficial use and proof of such beneficial use is filed with the State Engineer. The priority date of the licensed use is established by the date of filing of the original application.

Until 1957 a right to the use of the underground waters was forfeited when for a period of four years the owner of the right failed to apply the water to the use for which the right had vested, was appropriated, or was adjudicated.

Amendments enacted in 1957 and 1959 provide that the owner of a water right may apply to the State Engineer for an extension of time in which to put the water to beneficial use. Under these amendments the State Engineer may grant, for reasonable cause, such extensions of time not to exceed one year for each extension. It is important to note that a water right initiated prior to the inclusion of the area in which the well is located in a declared underground-water basin may be forfeited by 4 years of nonuse unless an extension of time in which to put the water to beneficial use is obtained.

The statutes provide that any person owning a water right initiated prior to the inclusion of the area in which the well is located in a declared underground-water basin may file with the State Engineer a declaration of his right setting forth the beneficial use to which the water has been applied, the date of first application to beneficial use, the continuity of the use, the location of the well, and, if the water has been used for irrigation purposes, the description of the land upon which such water has been used and the name of the owner thereof. Such records, or officially certified copies of such records, are prima facie evidence of the truth of their contents.

In the past the statutory provisions regarding the procedure for publication of notice, protest, and hearing, sometimes worked a serious hardship on appropriators whose wells suddenly failed. The 1959 session of the legislature amended the statutes to meet this problem. These amendments provide that the owner of a water right may drill a replacement well within 100 feet of his original well prior to application to the State Engineer in emergency situations which would result in serious economic loss, provided that he files application, or notifies the State Engineer of the facts by registered letter prior to drilling, and provided that he files formal application for a permit to drill the well within 30 days after drilling begins. This amendment provides that other water right owners may not enjoin the drilling of such a well but are limited to an action at law to recover damages, and to their right to protest the granting of a permit.

The amendment also provides that the owner of a water right may drill and use a replacement well more than 100 feet from his original well after he has made application, but without waiting for the completion of the publication and hearing, if the State Engineer finds after a preliminary investigation that the change does not impair existing water rights. Here again there must exist an emergency situation which would result in serious economic loss.

Also, the owner of a water right may drill and use a supplemental well upon making application, but without waiting for the publication and hearing in emergency situations, if the State Engineer finds after a preliminary investigation that the supplemental well would not impair existing rights.

ADMINISTRATION OF COLORADO GROUND WATER LAW

John H. Cuykendall[1/]

The administration of the Colorado Ground Water Act has not been a very successful experience. Two factors have caused this to be true. The limitations of the Act itself is the primary reason and, as ground water is generally supplementary to surface irrigation, it becomes a secondary interest to the user. There are certain areas in exception to this and in those areas the people are reluctant to face up to declining water tables and eventual depletion of the aquifer.

A brief summary of the promotion of ground-water legislation may point up some of the reasons for the limitations in the present law. Some twenty years ago a committee appointed by the State Bar Association attempted to write a ground water code, but after considerable time the committee bogged down and gave up. About that time the San Luis Valley began to have some loss of hydrostatic pressure in the artesian wells and called this to the attention of the State Agricultural Planning Committee. A subcommittee named to study the condition prepared a bill that was introduced, amended and passed by the Legislature in 1953. As presented, well drillers were required to drill and equip all wells in such a manner that the water flow could be controlled. The law was written in such a form that it applied only to the San Luis Valley or other high elevation valleys. Also by this law well drillers were required to have a license and notify the State of their intention to drill a well. Only the licensing of drillers with the requirement that they furnish logs on wells drilled survived the Legislature.

As there was a general opinion that Colorado did have a need for ground-water legislation the subcommittee continued to hold meetings. Personnel from the Ground Water Branch of the U. S. G. S. contributed data, several members of the legal profession contributed by making studies of the ground water laws of the other western states. Personnel from the Extension Service and the Engineering Department of Colorado State University furnished much information particularly by records of ground-water levels in areas when considerable ground-water use was developing.

By 1955 another ground-water code was prepared for consideration of the Legislature. The bill was placed before the Senate and proved to be one of the most controversial measures of the session. From hearings and debate four ideas were developed: (1) A wide division of opinion as to application of the several theories; prior appropriation, correlative or reasonable use and riparian or English doctrine. Each had its advocates and no compromise could be worked out. (2) Demand for considerable local control and administration. (3) Some type of State policy making Commission. (4) The State Engineer should be

1/ Chairman, Colorado Ground Water Commission

limited to only applying policies laid down by a Commission. The bill failed to pass the Senate by two votes.

The 1956 drought was affecting stream flow and industrial use of ground water was increasing. Farmers were having wells drilled wherever a prospect of securing additional water appeared. Many wells were installed and claims were made that they affected the surface stream flow. Considerable litigation over ground water appeared imminent. Under these conditions the subcommittee continued to work on a new code to be presented to the session in 1957.

Following the pattern developed in 1955, the 1957 bill provided for the creation of Ground Water Commission composed of eight members appointed by the Governor, two from each of the four major river basins. All were to be landowners, not less than four must be agriculturists, unbiased and without prejudice between ground-water and surface-water use. Ex-officio members, without vote, were the Governor, State Engineer and Director of the Colorado Water Conservation Board.

To the Commission was given power to determine policy in use of ground water, not otherwise decreed by court or statute. In any area, where investigation showed that ground water use had "approached, reached or exceeded the normal annual recharge" the Commission could form a "critical" or restricted district. Further burden on the aquifers designated as "critical" by construction of new wells was prevented. Development of new irrigated land could not be promoted, but domestic and stock wells were specifically exempted from this provision. In such a critical district a local advisory board of five members would be elected by the ground-water users. This board would advise and consult with the Commission in order to make the best use of the remaining ground water.

All irrigation, municipal and industrial wells then in use were to be registered with the State Engineer. A permit to drill would be required for all new wells. Well drillers were to be licensed and bonded. Prior appropriation would rule in critical districts with option to apply a form of correlative right when such a program was worked out by the Local Advisory Board and approved by the Commission. In many expert's opinion a good start toward a ground-water code was presented to the Law makers.

In the Legislature the application of prior appropriation was quickly cut out. A battle developed over the power of the Commission to close critical areas to further development. The Act, as finally passed, gave a local board the power <u>by unanimous action</u> to remove the designation immediately or its removal could be made by vote of two-thirds of the qualified votes at the end of any year's duration. Any police power over drillers by the State Engineer was left out of the Act except revocation of licenses. The only other control is through injunctive court procedure by the inherent police power of the State and this is too slow and too complicated to be effective.

When the Commission made the first effort to implement the provisions of the Act, an area on one of the tributaries of the South Platte River seemed to be in trouble. The area was entirely dependent on ground water for irrigation. For several years water table measurements had been made by W. E. Code, an engineer on the staff of Colorado State University. A large development of ground-water use had been made between 1945 and 1955. About 1950 a well users association had been formed. The records of Mr. Code were made available to the Association and much conversation on the subject of declining water tables took place. Under the auspices of the Association a survey was made in 1956 by both the Engineering and Economic Departments of Colorado State University. By production measurements of the wells in the area under study a withdrawal of 36,000 acre feet was indicated. Tables and hydrographs showing falling water levels in individual wells were shown. The report by the Economics Department pointed out that diminished production of the wells would eventually prevent profitable production of irrigated crops. A considerable acreage would be forced to return to dry farming resulting in much readjustment in farm units and many people would be forced to leave their land. This speaker was present when the reports were made and the reaction expressed after the meeting was "They don't know what they are talking about" or "Why worry, there is a lot of water in the ground."

From a rapid survey the Commission concluded this area was the most critical in the State. It appeared the well users were fully informed about the condition of the ground-water resource. An intensive study by the Commission confirmed the first impression that the area was using up the ground water much too fast for the economical good of the community. Drought had reduced yields of dry land crops and the Agricultural Adjustment Administration was reducing acreage planted to wheat resulting in much pressure to install more wells to bring land under irrigation. At a public hearing in the area those appearing were asked to give the original production and the present production of their wells as well as original static water table level and the present level. Where the witness could furnish these records a loss of production and lowering of water table was given indicating a general depletion of the area. On January 10, 1958, almost a year after the passage of the Act, the Commission designated this area as a "Tentatively Critical Ground Water District."

The Commission proceeded with the election of the Advisory Board as required by the Act and the "campaign" proved to be a hot one. Two slates of candidates for the Board were named, one pledged to require the Commission to remove the designation as a "Critical District" immediately. The opposing candidates promised to work with the Commissioners and wait for future developments before applying for the removal of the designation. The voters elected the candidate pledged to immediate action and vetoed the Commission by better than a two to one vote.

The section of the Act administered by the State Engineer has had some problems, namely in getting well drillers to take out licenses, to get permits to drill wells, and report logs after completion. In compliance with the Act we believe a great portion of the irrigation, municipal and industrial wells are registered.

Four sessions of the General Assembly have refused to make any change in the Act passed in 1957 except to extend the time of registration. In 1959-60, fiscal year funds were provided by the Department of Natural Resources and the Colorado Water Conservation Board for study of Ground Water problems and to make recommendations for further study and legislative consideration. One recommendation made in this report was the removal of the veto power of the local Board.

A number of suits involving ground-water use have been filed in the Colorado courts. Where a decision has been reached, the Court has applied the Prior Appropriation doctrine with some modifications as to quantity and lift. It seems now that Colorado will have a ground-water law written by the Court decree and not by legislative action.

Many people believe that when an area is showing a depletion of the water resource, the users should be able to set up districts under local control.

In this connection, a comment made during the Western Resources Conference at Colorado University in 1960 covers this situation very well. This comment was: "How bad will people need to be hurt before they will do something for their protection?"

No one attempted to answer this question.

GROUND WATER ADMINISTRATION IN ARIZONA

Charles C. Royall, Jr.[1/]

As Mr. Reynolds has said, "I appear here substituting for Mr. Lassen, State Land Commissioner for the State of Arizona, in which capacity there devolves upon him in addition to administration of State lands, the administration both of appropriable waters and ground waters."

First he has asked me to extend to the sponsors and to those persons in attendance at this 6th Annual New Mexico Water Conference his best wishes for a successful conference and his regret that he was unable to attend and participate in this panel discussion. To me, however, it is a pleasure to be here and to renew so many old friendships and make some new ones.

A little history appears appropriate as introductory to Arizona's ground water administration. When Mr. Lassen arrived in Phoenix in 1906, practically all of the irrigated land was irrigated from gravity flows of water diverted from brush dams placed in the rivers, consequently farming operations were geared to the amount of water which could normally be expected from that source.

Following construction of Roosevelt Dam on the Salt River completed in 1911 additional land was brought under irrigation adding to the 152,000 acres then under irrigation. This was not all good, for in the early '20's roughly 55,000 acres was becoming water logged in the lower Tempe country and in the area west of Phoenix. To cure that condition, drainage canals were constructed but were soon found to be unsuccessful. Thereafter, extraction of water by wells was started. All went fine for awhile and most, if not all the water logged lands were restored to a high state of cultivation but the extraction of ground water did not stop there. Soon more water was being removed than recharged was restoring.

The Eloy area was the first to experience difficulties. Studies by geologists and engineers showed that it would not be long before it would be uneconomical to farm due to the high cost of developing ground water. Other areas were soon in the same situation. It was under these conditions that the Arizona Legislature was asked to enact legislation establishing controls over ground water. After a period in which all drilling was prohibited in certain designated areas and many hectic special and regular sessions, Arizona's ground water code was evolved.

By this code the Land Department is charged with administration of "Ground Water" which is defined as "water under the surface of the earth regardless of the geologic structure in which

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1/ Assistant Attorney General, Phoenix, Arizona

it is standing or moving. It does not include water flowing in underground streams with ascertainable beds and banks.

The Department's duties appear to be four in number.

(1) A despository for compiling and maintaining records and factual data.

(2) Designating and altering the boundaries of ground-water basins.

(3) Designating and altering critical ground-water areas.

(4) The source of permits for new and for replacing or deepening irrigation wells within critical ground-water areas.

Before discussing these duties, it is probably well to clarify our terminology and for that purpose, we will use the definitions of the Code.

"Ground-water basin" means land overlying, as nearly as may be determined by known facts, a distinct body of ground water, but the exterior limits of a ground-water basin shall not be deemed to extend upstream or downstream beyond a defile, gorge, or canyon of a surface stream or wash.

"Ground-water subdivision" means an area of land overlying, as nearly as may be determined by known facts, a distinct body of ground water. It may consist of any determinable part of a ground-water basin.

"Critical ground-water area" means any ground-water basin as defined in paragraph 5 ("Ground-water basin") or any designated subdivision thereof, not having sufficient ground water to provide a reasonably safe supply for irrigation of the cultivated lands in the basin at the then current rates of withdrawal.

"Exempted well" means a well or other works for the withdrawal of ground water used for domestic, stock watering, domestic water utility, industrial or transportation purposes.

"Irrigation well" means any well or works for the withdrawal of ground water primarily used for irrigation purposes and having a capacity in excess of one hundred gallons per minute.

The 1st of the duties is fulfilled by a requirement that all wells existing prior to October 3, 1945 had to be registered, giving location, depth and other pertinent information and by the continuing requirement that any person desiring to drill any well give notice of intention to drill providing information as to location, depth, etc., and thereafter requiring the filing of the log by the driller.

The 2nd duty is being fulfilled as factual data for the determination becomes available.

The 3rd duty has been fulfilled in part by the designation of seven (7) critical areas with the prospect of several more in the near future. (This is a difficult duty to perform in that it is generally not popular with the people in the area until too late.)

Lastly is the problem of granting permits. Permits for new irrigation wells within critical areas are only granted for the irrigation of lands that were irrigated at the date the area was declared critical or within five years prior thereto.

A permit for replacing or deepening an irrigation well may be had on a showing that the well will no longer yield sufficient water to irrigate the land normally supplied by it within the five (5) years immediately prior to filing application for the permit.

In summary, primarily the law prohibits new irrigating wells in critical areas leaving restrictions on the use of water from existing or proper new wells to be suppled by the general Arizona Case Law, in particular the case of Briston vs. Cheatham, 75 Ariz 228, 240 P2d 185 (1952), rev. 75 Ariz 227, 255 P2d 173 (1953) which reaffirms the rules that percolating waters belong to the landowner and that the burden falls upon an appropriator of ground water to rebut the presumption that the water is percolating and established the doctrine of reasonable use as the test of the landowners right to use the water.

GENERAL PRINCIPLES OF GROUND WATER ADMINISTRATION IN TEXAS

R. M. Dixon[1/]

The primary objective of any form of administrative control of ground water is to provide for the optimum use of available ground-water supply, and concurrently provide for the equitable distribution of those ground-water supplies.

In some legal cases regarding ground water both in England and the United States there has been a separation in court holdings of two classifications of ground water: (1) underground streams and (2) percolating waters. Best hydrologic thought available suggests that there is no basis in fact for such a classification of ground water, and that all ground water is "percolating" in a physical sense.

Texas does not now have in its legal code provisions for state-wide administration and control of ground water. The courts, in implementing statutes on the books, have in general applied the principle of the law of capture in ground-water disputes. The following is a quotation from the Proceedings of the Water Law Conference, May 22-23, 1959, sponsored by the School of Law, University of Texas:

CASES ON UNDERGROUND WATER RIGHTS

"Houston & Texas Control Railroad Company v. East, 98 Tex. 146, 81 S.W. 279, decided in 1904, holds that W. A. East, the plaintiff in the case, had no remedy against the Railroad Company for drying up a water well on his property by drilling a well on adjoining property and taking large quantities of water for the operation of a locomotive and machine shop in the City of Denison. The case was decided on the authority of the English case, Acton v. Blundell, 12 Mees. & W 324, decided in 1843, holding that a plaintiff could not recover for drying up a spring on his land on account of water being diverted from the spring by underground channels dug in mining coal from defendant's land.

"The East case was followed in City of Corpus Christi v. City of Pleasanton, 154 Tex. 289, 276 S.W. 2d 798, decided in 1955. In that case the Court held that a water district should not be enjoined by the City of Pleasanton and others from producing four water wells drilled into the Carrizo sand in Atascosa County and flowing the water into the Nueces River in order to transport it over 100 miles down stream to be sold to the City of Corpus Christi.

"The Trial Court and Court of Civil Appeals found from the evidence that from 63% to 74% of the water discharged into the Nueces River failed to reach the diversion facilities of the City of Corpus Christi on account of evaporation and seepage. The Trial Court and Court of Civil Appeals found that this constituted

1/ Texas Member, Board of Water Engineers

"waste" of the water, which an adjoining property owner was entitled to enjoin in the protection of his rights to take water from the same formation. The lower courts held that, though the East case held that the taking of the water in such quantities as to dry up a neighbor's well was not actionable, the right of the overlying landowner did not extend to producing water from wells and wasting it. The lower courts relied both on a general rule of public policy, and on Art. 7602, Texas Civil Statutes, relating to waste of water from artesian wells by flowing the water into rivers, creeks and drains.

"The majority opinion of the Supreme Court in the Corpus Christi-Pleasanton case held that the release of water into the Nueces River was for the 'purpose' of making a beneficial use of the water and the fact that large amounts of it were inadvertently lost in transportation did not constitute waste within the meaning of the statute. The Court held that under the holding of the Supreme Court in Texas Company v. Burkett, 117 Tex. 16, 296, S.W. 273 (1927), the landowner had the right to take underground water from his land and transport it elsewhere for any beneficial use without reference to injury that might be caused to the wells of adjoining landowners.

"Three of the nine Judges of the Supreme Court dissented from the majority opinion in the Corpus Christi-Pleasanton case. Judge Griffin dissented only on the ground that the loss of up to 74% of the water in the course of transmission constituted "waste," and should be enjoined whether or not the waste was intentional. Judge Wilson, joined by Judge Culver, dissented both on the "waste" issue and on the general proposition that the East case should not stand in the way of protecting the correlative rights of landowners in water in an underground reservior or strata.

"The Court of Civil Appeals at El Paso, in Pecos County Water Control & Improvement District No. 1 v. Williams, et.al., 271 S.W. 2d 503 (Writ ref. s.r.c.), decided in 1954, held that the Water Control & Improvement District, which had a statutory appropriation of the waters of Comanche Spring at Fort Stockton, was not entitled to enjoin the diversion of the Comanche Spring water through wells drilled on adjoining property above the spring. The spring water had been used by the irrigators in the District for some 90 years. The case was decided on exceptions to pleadings. The Court of Civil Appeals held that if the waters in question were percolating waters that the diversion through wells was justified by the East case, and that the plaintiff's allegation that the waters in question were running through a well defined underground channel was not sufficiently specific, in that the exact measurements and course of the underground stream was not set forth.

"These cases by our Texas Courts hold that, though the right to take underground water is appurtenant to the overlying land, the landowner is not restricted in any way or under any conditions to the use of the water on or in connection with the land overlying the water bearing strata. In this respect, water rights in underground water are held to be different from all other water rights which appertain to the ownership of land. Both riparian and appropriative rights in all other water, whether in streams, the underflow of streams, lakes or water flowing in definite underground channels which are appurtenant to certain land may not be used for irrigation and other uses off of the land to which the right appertains if such use interferes with the use of water by other landowners having like rights."

In Texas the statewide administration of ground water, and for that matter of surface water, is complex because of the geographic, economic, social and hydrologic diversity of the State. This diversity results, of course, in part from the great size of the State, and in part from its location which places its East Texas counties in a humid climate and its West Texas counties in an arid environment.

The Texas Legislature recognized in 1949 the problem which would be encountered in attempting to provide equitable and adequate means of controlling ground-water development on a statewide basis. At that time the Legislature enacted a statute enabling the creation of underground-water conservation districts.

The UNDERGROUND WATER DISTRICT ACT (Art. 7880-3c) specifically authorizes these units of government to take administrative and authoritative action to promulgate rules regarding the conservation and use of underground water. The districts are created for the purpose of conserving, preserving, protecting, recharging and preventing waste of ground water from underground reservoirs. The act by which their creation is authorized provides for an appeal to the courts and a judicial determination of the validity and reasonableness of rules for these purposes promulgated by a district created in accordance with the statute.

Districts may be created by the Legislature, the State Board of Water Engineers, and individual county commissioners courts. Prior to creation of an underground-water conservation district, the Board of Water Engineers must determine that an underground-water reservoir, or subdivision thereof, having definable boundaries and meeting other pre-determined requirements, does in fact exist. Co-determined with the boundaries of the reservoir or subdivision, as delineated by the Board of Water Engineers, the water districts may be created. Under the terms of the statute authorizing their creation, each district is an autonomous regulatory entity with the geographic extent of its regulatory authority determined by the boundaries of the district. The district is a corporate unit which can own property and act in all ways as an entity having financial and legal responsibilities.

Since the passage of this legislation in 1949, the Board of Water Engineers has delineated 12 reservoir subdivisions and seven underground water conservation districts have been created. Five of these districts are extremely active and have, through their own initiative and utilization of their own tax resources, established an organization through which rules have been adopted regulating the development and protection of ground water within the district. In cooperation with other governmental units these districts have caused water surveys to be made within their boundaries and are, in general, exercising fully and responsibly the authority given them by the statutes.

The initial legislation passed in 1949 was amended in 1955 to strengthen the power of the districts with regard to well spacing, the regulation of production, and the prevention of waste. The amendment authorized well spacing as a means of preventing waste, lessening interference between wells, and preserving and conserving ground water. There are a few exceptions to the spacing authority given the districts, such as the application of spacing rules only to wells producing 100,000 gallons or more per day.

In enacting these statutes the legislature recognized the need for flexibility in ground-water administrative control to the end that these water supplies can be developed for the maximum benefit of the State. Establishment of the district program assumed that the local administration of ground-water control would permit this control to reflect local variations in hydrology and the impact of ground water use on the local economy.

The development of ground-water districts has been strong in Texas in the High Plains area where a large unconfined ground-water aquifer, the Ogallala formation, supports a vast economy of irrigated agriculture. Four districts on the High Plains operate actively to provide a strong regulatory program for the development of ground water within their boundaries. These four districts have adopted regulations which require permits before wells producing 100,000 gallons or more per day can be drilled, regulating the spacing of such wells and providing for control of pollution and waste within district boundaries. The authority of these districts is vested in elected officials, and administrative costs of the districts are supported by taxation on property within their boundaries.

Two serious problems with which the districts in the High Plains have had to deal have been (1) pollution of the ground-water reservoir by salt water produced with oil and gas in the area, and (2) the equitable distribution of the water available from storage as it is removed by pumpage from the water table aquifer.

Regulation of pollution by the districts has been spotty, but in general has taken the form of work through State authorities such as the Railroad Commission. In these instances studies have been made at the expense of the district to determine the extent of the pollution problem, and the technical data thus obtained has been referred to the Railroad Commission for authoritative action.

In other instances the districts have acted directly on their own initiative and under their own authority to end the disposal of brines produced with oil and gas into unlined pits on the surface of the ground.

The problem of providing an equitable distribution of the water supply has been approached generally through such means as well spacing, regulation of size and capacity of pumping equipment, limitations upon the rate at which permitted wells are produced, and education for most effective use of ground water. Well spacing is found to be beneficial as a conservation measure under conditions such as those found in the Ogallala reservoir for the following reasons: (1) interference between wells is reduced, (2) the drawdown between wells is minimized, (3) a higher ultimate recovery of water storage from the reservoir is made possible, and (4) pollution resulting from drawing in salt or other mineralized water under conditions of intensive pumpage is reduced.

While the High Plains area has been strongly influenced by the district program of ground-water administration, other areas where ground water is of primary significance such as the San Antonio area have also been affected by this administrative pattern.

A fifth district operating actively in Texas is the Edwards Underground Water Conservation District in that portion of the Edwards formation west of and including the City of San Antonio. Historically, vast spring flows emanating from the Edwards limestone along the Balcones fault zone have supplied a considerable municpal and industrial complex in this area. The intensive development of irrigated agricultural area west of San Antonio within the past few years has demonstrated a dramatic relationship between the flow of these great springs, the effects of the pumping wells, and the base flow of perennial streams in the area. Objectives of the Edwards District have been to achieve the equitable distribution of ground water supply available among the various economic interests of the area, and to conduct research into the possibility of increasing recharge to the reservoir by various means.

The physical relationship between ground water and surface water supplies in the hydrologic cycle make the separate discussion of ground water administration and surface water administration fairly academic insofar as ultimate goals are concerned. However, the integral relationship and interdependence of one supply upon the other cannot be adequately determined in an administrative framework until there is as much known of ground-water resources as surface water resources.

We have, however, in recent years recognized that the essential beginning which must be made if ground-water administration is to, in fact, meet its goals, is the study of the quantitative and qualitiative availability of the ground-water supplies in the State. A very long-range program designed to provide enough information to permit an appraisal of the availability for use and reuse of our ground-water supply is now underway. Completion of these studies should make it possible to create a climate of understanding of the need for the unified program of administration of ground and surface water.

The State Board of Water Engineers of Texas is, of course, vitally interested in the problem of wise administration of ground-water policy. We feel that ultimately legislative action, prompted by public awareness of the value of our ground water resources, will establish a broad statutory basis for the development and implementation of additional administrative authority in this field. Our role at the present time in furthering this aim is that of accumulation of as much knowledge about these resources as can be obtained in intensive study and investigation.

THE NATIONAL WATER SITUATION AS DEVELOPED BY THE SELECT COMMITTEE ON NATIONAL WATER RESOURCES

Nathaniel Wollman[1/]

The Senate Select Committee on National Water Resources was created in 1959 to study the national water problem and recommend policies to be followed by the Senate in enacting federal legislation. The Committee had some 90 studies made, held hearings over the country, and published the results in the form of hearing transcripts, committee prints, and a committee report. Upon publication of its report the Committee's work was completed and its staff discharged.

My talk will deal with the data on the supply of and demand for water developed for the Committee. My participation in this study was occasioned by the fact that prior to the Senate's creation of the Select Committee, Resources for the Future had already decided to embark on a study of water supply and demand. The Select Committee's staff, knowing of RFF's interest in the subject, proposed a partnership. In exchange for facilities provided by the Select Committee in acquiring data, RFF would supply the Select Committee with a preliminary report of its own study. The partnership was a happy arrangement for, I believe, both parties. I can speak for my side of the bargain, at least. With the Select Committee's help it was possible to acquire much more data than would otherwise have been available. RFF and I are deeply indebted to Senator Kerr, Chairman of the Committee, and to Theodore M. Schad, its Staff Director, for their support of the research task that was involved. The contribution of federal agencies in the man-hours of scientific work performed directly for the committee, let alone in the back-log of data accumulated in the files, cannot even be estimated. It is, in any case, a large multiple of the $100,000 which the Committee spent.

Method of Study

The study of the supply of and demand for water that served as the basis of the Committee's report was "preliminary" in two respects. It was preliminary in the sense that a final study incorporating essentially the same data, but reviewed and expanded, was still to be published. Under a grant from Resources for the Future to the University of New Mexico the review and expansion has proceeded, and I shall give you some of the additional results. It was also "preliminary" in the sense that incompatibilities between projected uses of water and the available supply had not been eliminated by some plan that either revised national projections or

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redistributed output among regions.

The study began by selecting an appropriate regional division of the United States. The Bureau of the Census Water Use Regions of the United States were adopted, modified by dividing the Missouri into an upper and lower region, separating the Upper AWR from the Lower, separating the Rio Grande and Pecos from the lower Rio Grande and the remainder of Western Gulf streams, and, finally, by separating the southern seven counties of California from the rest of the state. By making these changes, we attained greater homogeneity of each region in terms of water supply, facilitating any generalizations that we would be able to make.

Next we adopted national projections of population, gross national product, farm production, electric power production, and industrial output for 1980 and 2000. These projections were made for low, high, and middle paths of growth. So far only water use requirements based upon the middle projections have been published. The final report will deal with lows and highs as well.

The next task was to distribute national aggregates among the twenty-two regions. Population projections for each region were based upon dampened trends of ratios of regional population to U.S. population. Agricultural output, power production, minerals and major water-using manufactured goods were distributed by various federal agencies. The Department of Agriculture and the Bureau of Reclamation dealt with agriculture; the Federal Power Commission with electric power - both steam and hydro; the Bureau of Mines with mining and the refining of petroleum; and the Business and Defense Services Administration of the Department of Commerce with the manufacturing of food, pulp and paper, chemicals and primary metals. Public Health Service estimated municipal water requirements; Fish and Wildlife Service estimated water requirements for fish and wildlife habitat; the Soil Conservation Service estimated water required by soil and moisture conservation programs; the Corps of Engineers estimated navigation requirements.

The model of water use that was adopted for the study was designed to reveal determinate relationships between the available supply of water and the amount of water required to meet the levels of output projected for each region. We wanted to be able to say that if a designated level of output was projected for a given region the water supply would or would not be adequate. This meant that water "requirements" had to be framed in a manner that would avoid the indeterminacy inherent in measures of gross intake, since such a measure ignores the possibility of recirculation of water within a river basin. We defined water "requirements" as the sum of two elements: one, the amount of water lost to the atmosphere by evaporation and transpiration resulting from man's use. (This measure excludes wild or natural evaporation and transpiration, hence the losses we are concerned with are charged against runoff, rather than against precipitation.) A corollary of this measure is the stipulation that water quality is maintained at a level that allows recirculation within the basin and permits all uses to be met. Industrial wastes and municipal sewage can be treated, but even treated water will not be satisfactory for many uses unless mixed with high quality fresh water. This need for waste dilution is the second element of our requirement. The amount of waste dilution required depends upon three things: (1) the level of waste generated, which is a function of the level of output of waste generating products; (2) the level of treatment given to the waste effluent; (3) the quality of water desired after treatment and mixture of high quality water.

In estimating waste dilution requirements it was assumed that dissolved oxygen would serve as an index of the intensity of other pollutants. Given a designated level of treatment, if adequate dilution water were provided to assure an average of 4 milligrams per litre of dissolved oxygen, it was assumed that other pollutants would be adequately diluted. Although waste treatment levels up to 97½% removal of organic matter was assumed, no radically new technology was implied.

The relationship between waste dilution flows and level of treatment would be inversely linear were it not for the fact that at higher levels of treatment the conversion of organic matter into nitrogen and phosphorous fertilizes the receiving waters, stimulates the growth of algae, and creates a need for dilution water to offset the unfavorable effects of algal growth. Hence, as the level of waste treatment increases up to a certain point the need for waste dilution water decreases; but beyond that point, waste dilution requirements increase. The level of treatment at which this critical reversal takes place depends upon stream characteristics such as turbidity, velocity, depth, volume, length of reach, exposure to sunlight, and reaeration factors that vary from stream to stream and region to region. Based on findings that are still tentative, minimum required flows are found in the neighborhood of 90% to 95% treatment. In a few regions minimum flows are found at somewhat lower rates of BOD (biological oxygen demand) removal.

For a given level of economic output and population it is possible to estimate the loss of water to the atmosphere plus the amount of high quality water that must be flowing in the streams in order to mix with the effluent from treated waste. This sum is what is meant by "water requirements" or "water demand." The required flows are stipulated for the time of year in which waste assimilation is poorest, namely, the latter part of the summer for most regions. In other words, the requirement is the minimum amount of water that must be flowing in the stream during the period of low flow. This is a quantity that is not only free of ambiguity, but is framed in terms that make it directly comparable with available measures of supply.

Our measure of supply is a flow-frequency table for each region that indicates the flow equalled or exceeded 95% of the time, 90%, 80%, 70%, and 50% of the time, and the average flow. We know that by constructing enough storage, we can regulate a river so that its minimum flow approaches the level of average flow, measured at a designated point. Data on flow and storage were supplied by the U.S. Geological Survey. Average flows were adjusted to take into account increased losses from evaporation as a result of adding surface storage.

From the point of view of requirements we were able to stipulate the size of minimum flows that had to be provided, given the level of water-related economic activity and given the level of waste treatment. From the point of view of supply we had measurements of minimum flows under present regulation, and by how much minimum flows could be raised provided additional storage were constructed. With these two sets of figures at hand we could determine whether or not a region could meet its water requirements, and how much, if any, would be the deficit or surplus. We could also as shown later, estimate the costs of changing minimum flows and the costs of achieving designated levels of quality.

It is apparent that ground water did not figure explicitly into our measures of supply. We adopted the convention that our measure of supply was limited to the annual crop of water. Accordingly, it was assumed that ground and surface flows were inter-related, and that our measures of surface runoff indicated the annual water crop, after accounting for surface evaporation and interception by wild vegetation. By this assumption we ignore the supplies of water underground that are discharged into the oceans or that escape the United States across Canadian and Mexican borders. How large a quantity is involved for any border region is unknown. By measuring supply in terms of annual crop we also ignore the once-and-for-all withdrawal of water from underground reservoirs. Regions for which shortages of water are projected by 1980 may, in fact, be able to support indicated levels of activity by drawing down the water table. Such solution is, of course, temporary but may conceivably bridge a shift in water technology.

Measures of water use are restricted by two qualifications that may result in error of estimation of future water requirements. First of all, we did not take into account what effect higher costs of water would have on the quantity of water consumed. Second, our estimates of changes in water use per unit of output, based on technological improvement, were only crude guesses. A much more deliberate attempt was made in estimates for agriculture than for industry to account for the spread of knowledge as well as its discovery. The results, however, are scarcely more than intuitive extrapolations.

Our findings fall into two categories:

(1) the relationships between supplies and projected requirements in the twenty-two regions;

(2) the costs of alternative programs designed to yield water of designated qualities.

Supplies and Projected Requirements

The results of our estimates, for medium projections, can be summarized as follows:

In 1980 projected evapo-transpiration losses alone exceed average daily surface runoff in the southwestern part of the country and in the Upper Missouri (67 BGD (billion gallons per day) and 54 BGD, respectively). If we add the flows required for quality maintenance, aggregate required minimum flow in the Upper Missouri, Rio Grande-Pecos, Colorado, Great Basin, and South Pacific, amounts to 83 BGD, compared with an average daily flow of 54 BGD. Indicated requirements exceed maximum supply by 50%. By the year 2000, based upon the medium path of growth, total requirements are 113 BGD, compared with maximum supply of 54 BGD. By 2000, Western Great Lakes joins the original five as a water short region, largely because of the need for large waste dilution flows: 59 BGD required, 40 BGD available.

A word about the rate of growth implied in the medium projections. They assume that population and gross national product will grow at the average rate experienced over the last three decades. Senators Engle, Hart, McGee and Moss, in a supplemental statement in the committee report, objected to the fact that the projections used for Committee Print #32 were at these historical rates when in fact "water resource programs...must be paced to match demands generated by an economy growing at the rate of 4 to 5 percent rather than at the current rate of half that much."1/

If we project on the basis of a population growth that follows the path of the Bureau of the Census Series I, modified by increasing the amount of immigration from 150,000 yearly to 300,000 and if we allow GNP to grow at a rate of about 5% yearly, we have the high projections used for our study. As a result, by the year 2000:

(1) ten of the country's twenty-two regions are deficit areas;

(2) required flows in the original five regions amount to 181 BGD, compared with 54 BGD maximum supply. In addition to these five, western regions that are now deficit areas are the Upper AWR and the Western Gulf;

(3) the aggregate of deficits in all deficit regions is approximately equal to the aggregate of surpluses in all surplus

1/ Report, p. 137

regions. This implies that we should be able to meet 2000, high, national outputs with proper regional reallocation of economic activity.

Costs of Water

I would like now to indicate briefly some of the estimates of the costs of water.[1/] The costs I am talking about are restricted to those designed to provide minimum flows and waste treatment. Costs incurred to meet specific needs such as irrigation distribution systems, hydroelectric power plants, navigation locks, and water treatment plants have not been included.

We can construct cost curves for water on the basis of data we have. When we speak of supply, therefore, we can attach the economist's usual meaning to the word--a schedule of quantities related to costs. We do not have, as I have already indicated, equivalent information about demand. Until we know the elasticity of demand for water in terms of size of flow, variability of flow, and quality for each use, we cannot construct equivalent curves. The best we can do is estimate the physical requirements for a specified pattern of use on the basis of known technical relationships.

Neither representations of supplies nor demands are, properly speaking, curves, but multi-dimensioned schedules. Water provides an example of the difficulties created for the economist as a result of interdependence between supply and demand. A supply curve for water cannot be constructed until we first know the uses to which the water will be put, since use determines both loss and quality change, and these, in turn, determine the level of flow and level of treatment that are needed in order to assure water of a designated quality after use and treatment. If there is an elasticity of demand greater than zero--i.e., if price paid for water affects the uses to which it is put and the quantities of these uses--we must solve simultaneously the equations that describe the supply and demand functions. At present we do not have the necessary information for reaching such solutions. Furthermore, since such solutions are normally derived from static relationships, whereas the world that generates the observable measures is a dynamic one, we can never directly observe the proper values for our equations unless we use dynamic models on the one hand or achieve a static world on the other. Our conclusions whether they are relationships between flows required and flows available, or between type of program and costs of program, are based upon holding a number of variables constant and drawing our inferences from a restricted set of conditions.

1/ These figures are still tentative, as well as the estimates of flow requirements.

To meet medium projected requirements between now and 2000 we shall have to raise treatment levels to between 90% and 97½% BOD removal in most regions. At present there are many points at which raw, untreated sewage is being dumped directly into receiving waters.

We shall have to increase our reservoir capacity by an amount that will more than double present capacity. In some eastern regions we shall need as much as 40 times the capacity we now have.

Annual costs of treatment and storage to provide water of adequate quality will be between $4 and $5 billion at 1960 prices by the year 2000. Cumulative capital costs by 2000 will be about $100 billion. Actual costs will depend upon the programs we adopt. For example, if we emphasize waste dilution rather than waste treatment, the capital costs of storage needed to assure the dilution will be about $45 billion. If we emphasize treatment rather than storage, the costs of storage will only be about $14 billion. Treatment costs will vary in the opposite manner. If we emphasize storage, capital costs of treatment facilities, will be about $74 billion. If we emphasize treatment rather than storage, capital costs of treatment will be about $93 billion.

Since the costs of treatment and storage do not vary by an inversely proportional relationship, the program that minimizes the costs of treatment and storage taken together will emphasize treatment. For such program the capital costs of storage are about $18 billion and the capital costs of treatment are about $82 billion, for a total of $100 billion. By comparison, the program that emphasizes storage and minimizes treatment would cost about $18 billion more.

These are not forecasts but are, instead, estimates of what will happen if we make certain choices. The estimates themselves are subject to modification if we develop new technologies of water use and waste treatment, or if we grow at a different rate from that postulated, or if we shift our consumption from the projected pattern of goods and services to others that use and pollute either more or less water. Finally, our estimates would be subject to revision upward if we choose a higher standard of water quality, or downward if we choose a lower standard.

We need to know more about many things before we can speak with assurance about the various estimates that emerged from the Select Committee's research effort. A few examples will illustrate these needs.

(a) the inter-action between ground and surface water movement, and the possible substitution of ground storage for surface storage.

(b) the effect of recirculation on the rate of water loss and quality of waste discharge.

(c) the effects of rising costs of water on the demand for water.

(d) the effects of stabilizing flows on the output of hydroelectric power and the place of hydro in the total energy picture.

(e) the effects of waste discharge and waste dilution flows on estuarine waters and the productivity of commercial fisheries.

Need for a well conceived national water resource program based upon adequate information can hardly be overstressed. Its urgency is indicated by the results that are yielded by the high projections for the year 2000, which imply that by that year our water supply will be fully utilized and under full regulation. Since the high projection leads the medium projection by about one generation, we do not have much spare time even if growth follows the medium path. At the lower rate of growth we will be at the same point of full use by the year 2035.

LITTLE DROPS OF WATER

Roy Calkins[1/]

Our subject today is LITTLE DROPS OF WATER that are in the Lincoln National Forest. Where they come from, what happens to them when properly cared for, what happens to them when they are wasted before they can be put into their natural storage and where they are stored.

To make a reasonable understanding of our LITTLE DROPS OF WATER we must take into consideration many things.

First, where do our LITTLE DROPS OF WATER come from? All the LITTLE DROPS OF WATER come from rain.

Second, what happens to the LITTLE DROPS OF WATER when they are properly cared for? Now let us go to the record put out by our United States Department of Commerce Weather Bureau and find out the number of these LITTLE DROPS OF WATER. From 1902 to 1930, a period of 28 years, there was an average of 23.77 inches of rain per year. This flowed into the natural resource reservoir in Lincoln National Forest. There is a natural resource reservoir drainage by flowing springs to the towns of La Luz, Tularosa, Cloudcroft, Alamogordo, Mayhill, Lower Penasco, Hope, Orgrande, Pinon, and Dell City areas.

And, finally, what happens to the LITTLE DROPS OF WATER when they are wasted before they can be put into their natural storage? We will go back to the government record and find out how many LITTLE DROPS OF WATER fell in the period of 1930 to 1960. There was an average of 26.34 inches of rain per year, that is 2.57 inches more than fell in the period of 1902 to 1930.

These examples are the best ways I can explain the misuse of our LITTLE DROPS OF WATER. The production of animals and farming have been reduced. The Forest Service permits 17 head of cattle now to the same amount of land as they did in 1920 for 80 head of cattle. There are many, many orchards that have died because there was not enough drainage from the natural resource reservoir.

Now we suggest take steps to immediately get back our natural resource reservoir, remove the weed trees and clean the debris so our forest will be more beautiful and make a better recreation area with our LITTLE DROPS OF WATER. There are many, many LITTLE DROPS OF WATER wasted by the lack of knowledge.

1/ Farmer, Sacramento, New Mexico