INVESTIGATION OF THE FEASIBILITY OF SECONDARY RECOVERY OF GROUND WATER FROM THE OGALLALA AQUIFER

A Report to the Sixty-Ninth Texas Legislature

Based on a study completed under
contract with the High Plains Underground Water
Conservation District No. 1

LP-202

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The Governor of Texas
The Lieutenant Governor of Texas
The Speaker of the House
The Legislature of the State of Texas

Transmitted herewith is a report which the Texas Department of Water Resources was directed to prepare pursuant to a rider attached to Senate Bill 179, Sixty-Eighth Legislature. Staff of the Texas Water Development Board have been assigned the former Department's responsibilities related to ground-water investigations and have assumed the responsibility for preparation of this report.

The data resulting from investigations of the feasibility of enhanced recovery of ground water in the Ogallala Aquifer indicate that the injection of air into the unsaturated zone of the aquifer results in increasing the volume of water recoverable from the aquifer. The Board will be pleased to supplement the material presented herein with additional details at the request of any interested reader.

Respectfully submitted,

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FOREWORD

Effective September 1, 1985, the Texas Department of Water Resources was divided to form the Texas Water Commission and the Texas Water Development Board. A number of publications prepared under the auspices of the Department are being published by the Texas Water Development Board. To minimize delays in producing these publications, references to the Department will not be altered except on their covers and title pages.

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SUMMARY OF INITIAL WORK PHASE

Introduction

The Ogallala Formation of the High Plains is composed of individual particles of clay, silt, sand, and gravel. The spaces between these particles may be completely filled with water. Where this occurs, the formation is said to be saturated with water. The first recovery, development, of water is by pumping wells. As water is removed by a well, gravity causes some of the water to drain from between the sand grains to replace the water removed by the pumping. This water is called gravity water. The water that remains in the formation after gravity water drains is called capillary water. This is water that surrounds individual particles in a thin coat or is held between particles by various forces such as surface tension. For the Ogallala, only one-third of the water that is between the sand grains is gravity water, meaning that much water remains in the ground. This research was aimed at discovering a second method of water development, called secondary recovery.

In 1980, the 67th Texas Legislature appropriated $250,000 to the Texas Department of Water Resources to investigate the feasibility of the release of water from the wet sands of the Ogallala Formation on the High Plains of Texas for future recovery by wells completed in the underlying portion of the formation that is saturated with water. This investigation has been conducted by the High Plains Underground Water Conservation District through contract with the Texas Department of Water Resources and in cooperation with Texas Tech University's Water Resources Center, Texas A&M University, and the Texas A&M University System Texas Agricultural Experiment Station.

Objectives

In the initial work phase of the project, five objectives were set: (1) determine the amount of capillary water in storage, (2) identify available or emerging technologies for recovery of the capillary water, (3) evaluate capillary water recovery techniques, (4) develop plans to field test a recovery technique to recover the capillary water, and (5) test the recovery technique at a field site.

Results

In order to aid the accomplishment of these five objectives, the Department drilled holes at seven locations to collect formation core samples (Figure 1). Analyses were then performed on these samples to determine the percent moisture, by volume, in each core sample. In conjunction with these analyses, District staff set out to determine the amount of wet (non-saturated) formation material between the root zone (extending ten feet below land surface) and the 1980 water table. It was determined from the thickness map made for the area that 3.36 billion cubic acres of wet formation material existed in the Ogallala Formation in the High Plains of Texas (Figure 1). Using the results of the core analyses which showed an average moisture content of 25.9 percent, by volume, in the wet formation material, it was estimated that there was 840 million acre-feet of capillary water in storage. Additional mapping and calculations were made of the quantity of capillary water which would be in storage in the Ogallala Formation in the wet formation section after the gravity water which is now in storage in the saturated part of the Ogallala is removed. It was determined that an additional 640 million acre-feet would be in storage as capillary water. The total of the two amounts is 1.46 billion

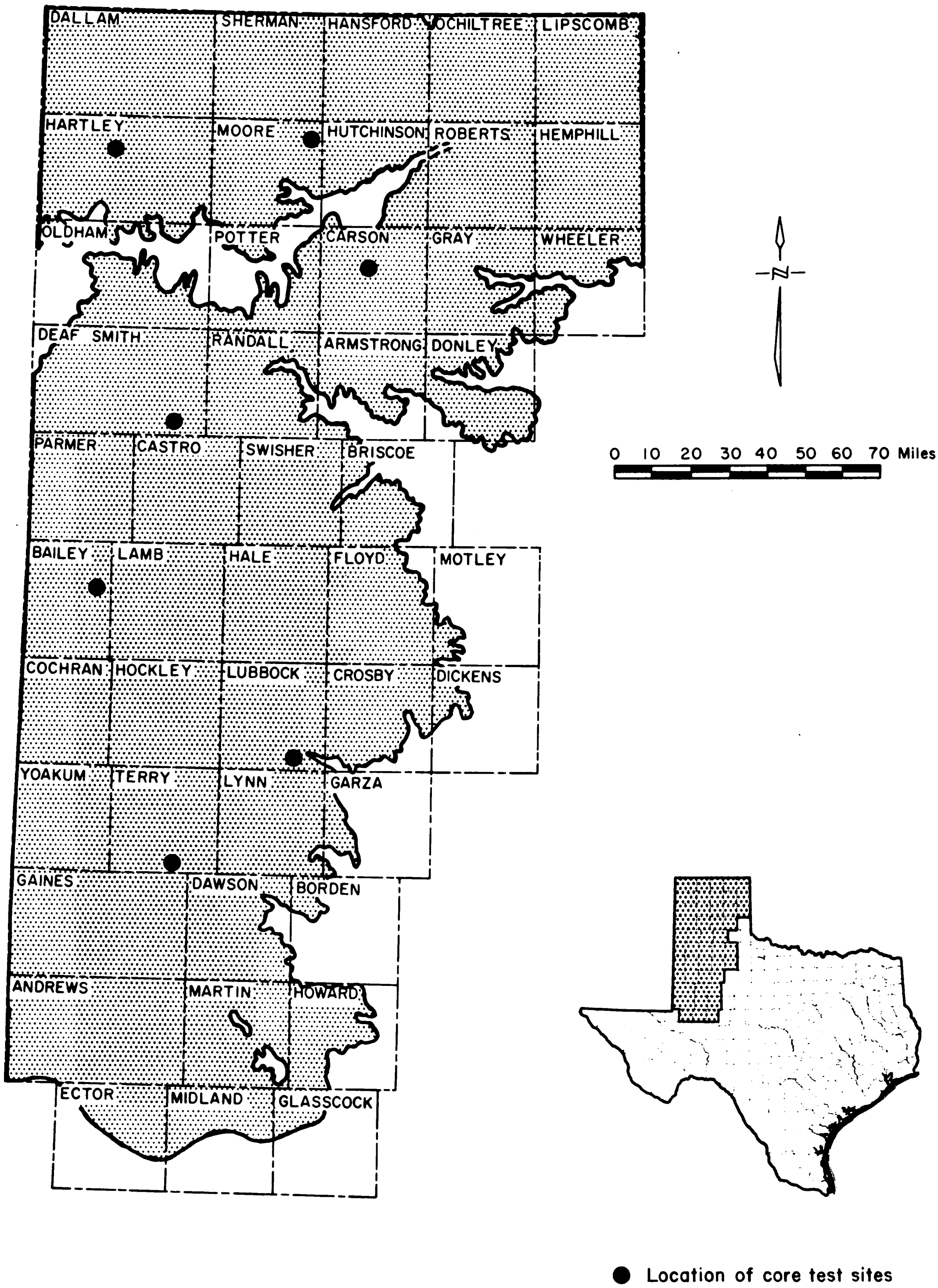

Figure 1

Location and Extent of the High Plains Aquifer in Texas acre-feet of water, which is the quantity that is or will be in storage as capillary water in the Ogallala Formation on the High Plains of Texas.

An exhaustive literature review was also conducted to find reports of previous research projects of this nature. No articles pertaining directly to the recovery of capillary water were found; however, five potential secondary recovery techniques were identified. The identified techniques were air drive, surfactant/foam, thermal, vibration, and electro-osmosis. Through analysis of these techniques, it was determined that air drive showed the most promise, with the other four being currently economically infeasible.

On the basis of the quantities of capillary water in storage and the selection of air drive as a potential recovery technique, three field tests were then conducted from December 1981 to June 1982. Two of the field tests were performed on Mr. Ronald Schilling's farm west of Slaton in Lubbock County, Texas and the third test was conducted on a farm south of Idalou in Lubbock County, Texas on land owned by Mr. Clifford Hilbers. The results of these tests indicated that approximately 25 percent of the water in capillary storage was released to the underlying saturated zone of the aquifer for future recovery by wells. Calculations of the cost of the field tests as applied to the amount of water initially made available for future use showed an approximate cost of $50 per acre-foot of water released.

During the initial work phase, attempts were also made to model the physics of two-phase flow in a porous medium where both air and water appear to move simultaneously.

In November 1982, the Department presented to the Legislature a report titled "Investigation of the Feasibility of Secondary Recovery of Ground Water from the Ogallala Aquifer." The report summarized the results of the initial phases and recommended that the research be continued.

SUMMARY OF THE SECOND WORK PHASE

Introduction

In 1982, the 68th Texas Legislature appropriated $100,000 to the Texas Department of Water Resources to continue the secondary recovery research effort. The Department contracted with the High Plains Underground Water Conservation District No. 1 to perform the study.

Objectives

(1) Investigate the Nature of Processes Causing Capillary Water to be Released.

In this regard, the Department agreed to reimburse the District for funds to cover contracts with:

(a) Texas Tech University, to construct a digital model of the response of an aquifer to air injection and the resulting report of this study titled "Mathematical Modeling of Secondary Recovery of Water from the Vadose Zone by Air Injection", and

(b) Texas Agricultural Experiment Station, to (1) review literature on two-phase flow of fluids, (2) develop a laboratory apparatus to determine certain hydraulic parameters related to unsaturated flow, (3) determine values for certain hydraulic parameters for aquifer material from the air injection site near Idalou, Texas, (4) provide consultation and output to the District in developing an improved mathematical model of the air injection process, and (5) complete the report on the results of this study titled "Recovery of Water from the Unsaturated Zone of the Ogallala Aquifer by Air Injection: Physics of Flow."

(2) Conduct pilot program(s) to test one or more of the capillary water-recovery techniques.

In this regard, the Department agreed to reimburse the District for funds expended in connection with the tests conducted at a secondary recovery site near Wolfforth. This reimbursement consisted of funds remaining after reimbursement of the District contracts described in Objective No. 1 above; and not to exceed $100,000, the total of the contract between the Department and District.

Results

A five volume series of reports was prepared describing the second work phase of the "Continuing Studies of Secondary Recovery of Capillary Water". The reports are as follows:

(1) "Executive Summary", Report 1 of 5, High Plains Underground Water Conservation District No. 1.

(2) "Continuing Studies of Secondary Recovery of Capillary Water", Report 2 of 5, High Plains Underground Water Conservation District No. 1.

(3) "Wolfforth, Texas Air-Injection Pilot Project Data Compilation", Report 3 of 5, High Plains Underground Water Conservation District No. 1.

(4) "Recovery of Water from the Unsaturated Zone of the Ogallala Aquifer by Air Injection: Physics of Flow", Report 4 of 5, Texas Agricultural Experimental Station.

(5) "Mathematical Modeling of Secondary Recovery of Water from the Vadose Zone by Air Injection", Report 5 of 5, Texas Tech University.

Report 1 of 5, "Executive Summary", presents (1) a brief summary of the initial phase of the project including results of the core analyses and a determination of the percent of moisture, by volume, which was stored in the formation samples as determined both by Texas Tech University and by the Texas Department of Water Resources, (2) maps illustrating the changes in water levels which have occurred at various time intervals in the area of the secondary recovery tests conducted during the past five years, (3) an economic analysis showing the approximate cost of the air injection process had it been conducted by the local landowner/operator, after deletion of costs associated with the monitoring effort, (4) the effect of air injection on water quality, based on chemical analyses of water samples collected at the Wolfforth test site, (5) the effects of air injection on land subsidence, based on data obtained from Idalou and Wolfforth, and (6) an attachment titled "Criteria for Selection of Location for Air-Injection Well, Well Design, and Construction", which is designed to help the landowner/operator interested in private ventures in the use of air injection to release capillary water.

Report 2 of 5, "Continuing Studies of Secondary Recovery of Capillary Water", presents discussions on (1) previous work on secondary recovery, (2) a synopsis of results, conclusions, and recommendations, (3) the theory of capillary storage and mechanism for removal of water, (4) a summary of on-going literature review and physical and mathematical modeling activities, (5) a description of the Wolfforth test and results, (6) the effects (if any) of air injection on ground-water quality, (7) the effects (if any) of air injection on land subsidence, (8) the technology and economic feasibility of secondary recovery, and (9) the status of secondary recovery research.

Report 3 of 5, "Wolfforth, Texas Air-Injection Pilot Project Data Compilation", contains a complete compilation of data collected for the period October 1983 through March 1985 in connection with the air-injection tests conducted at Wolfforth, Texas. The data consist of (1) water-level observation well data, (2) air-monitoring well data, (3) electrical impulse logs, (4) water well drillers logs, (5) operating times and injection-well head pressures, and (6) barometric pressure readings.

Report 4 of 5, "Recovery of Water from the Unsaturated Zone of the Ogallala Aquifer by Air Injection: Physics of Flow", presents discussions on (1) the secondary recovery concept, (2) the replacement of water by air in porous media, (3) similitude criteria for two-phase flow in porous media systems, (4) sand tank models, (5) numerical model of two-phase flow, (6) design of a sand tank, (7) design of two-phase permeameter, (8) Idalou site porous media properties, and (9) summary and conclusions.

Report 5 of 5, "Mathematical Modeling of Secondary Recovery of Water from the Vadose Zone by Air Injection," discusses the construction of a mathematical model capable of reproducing the space and time distribution of air pressure and water content observed in the field experiment of air injection into the vadose zone. The formulation of flow equations, numerical solution methods utilizing three solution schemes, and the summary conclusions and proposed future modeling efforts are also included.

The preceding briefly summarizes the five reports prepared in connection with the second phase of the secondary recovery research effort. Copies of these reports are available should more detail be needed on any aspect of the effort.

CONCLUSIONS AND RECOMMENDATIONS

Below is a summary of the Department's assessment of the secondary recovery research programs, thus far, and highlights of the results from Wolfforth, Idalou, and Slaton field programs, laboratory testing, and mathematical and physical modeling.

Results

* Secondary recovery of capillary water can be accomplished.
* There is an estimated potential of 1.46 billion acre-feet of capillary water underlying the High Plains of Texas.
* Lab tests indicate that the use of surfactants/foams, thermal, vibration, and electro-osmosis mechanisms can be used to free capillary water - but are expensive.
* Injection of compressed air currently appears to be the most economical and successful mechanism for secondary recovery.
* Twenty-five to thirty percent of the capillary water in storage can be released under induced pressures of less than eight psi at the injection point, as observed in field and laboratory testing.

* Secondary recovery field programs can be constructed to recover capillary water.

* Secondary recovery of ground water is site specific.

* Commercially available equipment can be used for secondary recovery.

* Secondary recovery appears to be more successful/economical in fine-grained formations.

* Secondary recovery does not necessarily require an air-tight "confining cap" in the aquifer.

* Extensive gravel deposits within the test site tend to reduce the results of air injection.

* Test results indicate that a means of accurately measuring in-situ formation moisture changes as a function of air injection is needed to better explain the apparent rise in water levels at the test sites.

* Mathematical modeling of the secondary recovery process is difficult due to site-specific data requirements.

* Mathematical solution techniques and required matrixes to model secondary recovery are too complex and large for standard mainframe computers - super computers are needed.

* Construction of a physical model that adequately represents the secondary recovery process is not practical.

* At this time, secondary recovery of ground water is economically feasible for municipal and industrial purposes.

* Water drainage from capillaries occurs for months/years after short-term injection periods, i.e., there are extended benefits to short-term air injection.

* Higher air-injection rates and volumes result in larger areas of influence.

* Clay layers appear to be better confining caps than other rock layers.

* Secondary recovery of ground water does not appear to affect ground-water quality.

* Secondary recovery of ground water does not appear to cause land subsidence.

* Changes in atmospheric barometric pressure influence pneumatic formation pressure and water table fluctuations.

* Secondary recovery is successful even in formation material that has a moisture content less than field capacity.

Conclusions

The Texas Legislature has funded investigations of the feasibility of secondary recovery of ground water from the Ogallala Formation on the High Plains of Texas. The specified investigation topics have been addressed. Estimates of the amount of water stored in the unsaturated zone have been made. Processes that release water have been identified and some progress has been made on explaining how the application of air pressure results in the secondary recovery of ground water. Monitoring techniques have been developed, and secondary recovery technology has been field-tested at three sites. Each test appeared to result in the secondary recovery of water. Design criteria have been developed for future secondary recovery applications. Secondary recovery appears to be economically feasible for municipal and industrial water-supply purposes.

Recommendations

It is now considered appropriate to enter into another phase of the investigation. Previous work has shown that secondary recovery can be accomplished by air injection, but reasons for the release of capillary water are not sufficiently understood. Other research questions still unanswered include:

* Injection temperature effects on secondary recovery.
* Effects of atmospheric barometric pressures on secondary recovery.
* Formation moisture changes before, during, and after secondary recovery.
* Commercial feasibility of secondary recovery.
* Mechanical efficiency of air injection into a formation.
* How to effectively model (mathematical and physical) secondary recovery.

* Measurement of in-situ parameters such as air and water permeability and soil moisture content.

* Benefits of simultaneous area-wide injection as opposed to a single air-injection site.

* Effects of formation type on secondary recovery.

* Displacement and movement of water in the saturated zone during injection periods.

* Effects of the degree of heterogeneity of formation material on secondary recovery.

* Application of secondary recovery technology to formations other than the Ogallala Formation.

* Efficiency of short-term versus long-term air injection.

* Optional design of air-injection wells such as screen size, blocking of formation material, injection depth, and drilling and development procedure.

* Maximizing pressure fronts or movement through formation material.

* Accurate definition of two-phase flow (water and air) through porous material.

* Specific occurrence and distribution of capillary and gravity water in the vadose zone.

Many of these topics are of a fundamental as opposed to an applied scientific nature and are the type of research topics that are normally investigated by universities and the U.S. Geological Survey. Therefore, it is recommended that further work on secondary recovery by research institutions be directed at understanding why application of air pressure results in release of capillary water. With a better understanding of the physical processes, field application designs can be refined and improved to obtain optimum results with the least expense.