UNITED STATES DEPARTMENT OF THE INTERIOR
Harold L. Ickes, Secretary

GEOLOGICAL SURVEY
W. C. Mendenhall, Director

Water-Supply Paper 796

CONTRIBUTIONS TO THE HYDROLOGY OF THE UNITED STATES 1937

NATHAN C. GROVER, Chief Hydraulic Engineer

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Water-Supply Paper 796—A

METHODS OF LOCATING SALT-WATER LEAKS IN WATER WELLS

BY

PENN LIVINGSTON AND WALTER LYNCH

Prepared in cooperation with the
TEXAS BOARD OF WATER ENGINEERS

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N. C. Grover, Chief Hydraulic Engineer

METHODS OF LOCATING SALT-WATER LEAKS IN WATER WELLS

By Penn Livingston and Walter Lynch

Abstract

In localities where highly mineralized water is present in beds above and below the beds that yield the supplies of fresh water it is necessary to be able to locate leaks in wells in order to know whether the wells are being contaminated through holes in the casings or whether the fresh water supply is failing. Four general methods of detecting salt-water leaks have been used. In the pumping method, samples taken at measured time intervals while the well is being pumped show by their progressive change in salinity if salt water is being drawn in. In the velocity method, which is suitable for use only in artesian wells, a current meter lowered into the well indicates the location of possible salt water leaks by determining the levels at which there are changes in the rate of upward movement of the water. In the sampler method a container lowered into the well brings up a sample from any depth desired for analysis of its chloride content. The electric conductivity method, for which special apparatus was designed, has been used successfully in the Winter Garden area and Kleberg County, Tex., and in Sarasota County, Fla. The procedure in this method was to lower a pair of insulated electrodes into the well and measure the resistance of the water between them with the Wheatstone bridge or, in waters low in chloride, to apply a direct current of low voltage and measure the current flowing between the electrodes by means of a milliammeter. The instruments showed a marked increase in the conductivity of the water as the electrodes passed from fresh to salt water in the well, leaving no doubt as to the location of the leaks.

INTRODUCTION

During recent years the United States Geological Survey has been called upon to investigate several areas in which the water obtained from wells has been contaminated by salt water. Many of these water supplies are vitally important for industry, public supplies, or irrigation, and the infiltration of highly mineralized water has proved objectionable.

In addition to the damage represented by the loss in yield and quality of crops irrigated with highly mineralized water, much more serious loss may result through the ultimate abandonment of valuable farm lands that become so heavily saturated with salt that further crop production from them is impossible.[1/] Definite limits for the content of salt

1/ Burgess, P. S., Alkali soil and methods of reclamation: Univ. Arizona Bull. 12, 1928.

in water to be used for irrigation have not been determined, as the limit of safety is subject to wide variation: much depends upon the character of the soil, the drainage of the soil, the quantity of water used, and the frequency of the irrigation.[2] Highly mineralized water is unfit for use in boilers, for ice making, and for other industrial uses. The contamination by salt water of wells used for public supplies presents a serious problem to municipalities dependent upon such sources, especially where it seems probable that some of the wells that have been developed at considerable expense may have to be abandoned. To be suitable for domestic use water should not contain over 250 parts per million of chloride[3] (one of the two elements of common salt, sodium chloride) and preferably should contain much less than this amount. A chloride content of 400 to 500 parts per million, however, though noticeable to the taste, is not especially disagreeable, and human beings can tolerate water containing more. Ordinary ocean water contains between 19,000 and 20,000 parts per million of chlorides.

Salt water has a highly corrosive action on well casing, thereby shortening the life of the well. It also corrodes the pumping equipment, thus reducing the efficiency of the pump, and increasing the cost of operation. Ultimately the loss of efficiency and increased cost of operation become so great that the pumping equipment must be removed from the well and repaired at considerable expense.

It is evident, therefore, that the contamination by salt water of a water supply obtained from wells represents a serious problem that may affect vitally the economic future and possibly the very existence of entire communities. Much concern has been expressed by residents in such localities as to whether the fresh-water reservoir is becoming contaminated or whether highly mineralized water from some upper water-bearing bed is entering the well because of faulty well construction. As very little work had been done in this field of investigation it became necessary to develop methods for determining the extent of the contamination and the points at which the highly mineralized water entered the wells. It is the purpose of this paper to present the various methods that have been used in studying the problem.

2/ Scofield, C. S., The alkali problem in irrigation: Smithsonian Inst. Ann. Rept., 1921, pp. 213-223. Breazeale, J. F., A study of the toxicity of salines that occur in black alkali soils: Arizona Univ. Bull. 14, 1927.

3/ Drinking-water standards, U. S. Public Health Service, 1925.

AREAS STUDIED

Among the areas in which contamination of wells by salt water has been studied by the United States Geological Survey are the Atlantic City area, N. J., the Winter Garden area and other areas in southwestern Texas, Sarasota County, Fla., and areas in Iowa.

The work in southwestern Texas was done by the Geological Survey in cooperation with the Texas Board of Water Engineers as part of the study of ground-water resources of the State. Explorations of wells with the current meter were made by A. G. Fiedler and Penn Livingston in the Winter Garden area in July 1930, and the electrical-conductivity method was developed and used in that area by Mr. Livingston and Walter Lynch in the fall of 1930 and in 1931. The experience gained was utilized in designing the apparatus used in Kleberg County, Tex. in the winter of 1932-33 by Mr. Livingston and T. W. Bridges and that used in Sarasota County, Fla. Fla., in 1932 by V. T. Stringfield and Mr. Fiedler.[4/] These investigations were conducted under the general direction of O. E. Meinzer, geologist in charge of the division of ground water, United States Geological Survey.

In October 1934 a survey of wells in Iowa that yield highly mineralized water was begun by the Iowa Geological Survey in cooperation with the United States Geological Survey, and the equipment used in Florida was made available for that investigation.

In view of the fact that some of the apparatus was designed for specific projects, all the apparatus will be described and the results discussed.

METHODS OF INVESTIGATION

There are four general methods of locating salt-water leaks in wells. For convenience the methods may be designated the pumping method, the velocity method, the sampler method, and the electrical-conductivity method. The pumping method consists of pumping the well and noting the change that takes place in the salt content of the water discharged from the well as pumping progresses. In the velocity method the location of leaks is determined by finding with a current meter the place at which

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4/ Stringfield, V. T., Exploration of artesian wells in Sarasota County, Fla.: Florida Geol. Survey 23d-24th Ann. Rept., pp. 195-227, 1933. Fiedler, A. G., Deep-well salinity exploration: Am. Geophys. Union Trans. 14th Ann. Meeting, pp. 478-480, June 1933.

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any measurable movement of water takes place in the well; to use this method in a flowing well it is desirable to extend the well casing above the surface until the flow ceases. In the sampler method water samples are taken at different depths in the well and their salt content determined. The electrical-conductivity method is based upon the principle that salt in water increases its electrical conductivity; by observing the depth in the well where the electrical conductivity of the water increases markedly it is possible to determine where the salt water enters.

Pumping method

In the pumping method samples of water are taken at frequent measured time intervals, beginning with the starting of the pump. The first samples are taken at intervals of a few seconds; later the intervals are lengthened because the salinity of the water usually becomes more nearly uniform as pumping continues. The samples are tested for chloride with an ordinary field outfit of silver nitrate and potassium chromate solutions. Then curves are plotted showing the change in salinity that occurs in the water as pumping progresses. The best results are obtained when the tests are run after the wells have been idle for some time.

The pumping method of investigation is applicable only to the study of wells that can be pumped readily or that have a natural flow. It serves admirably to show the degree of contamination by salt water and whether or not the salt water is entering through the fresh-water beds. It is not possible with this method to locate the exact position of a leak in the casing, but in many wells the approximate position of the leak can be determined by noting the quantity of water discharged between the starting of the pump and the appearance of salt water in the discharge.

In the Atlantic City area, where the beds yielding fresh water are overlain by beds containing salt water, Thompson[5/] used the pumping method to determine whether the salt-water contamination occurred by direct leakage from a salt-water formation through the casing of the well being pumped; whether the salt water came from nearby wells into which there was salt-water leakage; or whether the contamination was due to direct percolation of salt water into the fresh-water formation.

5/ Thompson, D. G., Ground-water supplies of the Atlantic City region: New Jersey Dept. Cons. and Devel. Bull. 30, pp. 96-112, 1928.

In the Winter Garden area of Texas the formation yielding the fresh water lies between two formations that ordinarily contain water that is highly mineralized, chiefly by common salt. Therefore, most of the wells must be tightly cased through the overlying formation to exclude undesirable water from above, and they should not be drilled into the underlying formation. In this area the pumping method was used successfully in about 40 wells and showed in every test that the salt water was coming through defective casings and not from the fresh-water formation. In nearly all the wells the test gave definite information regarding the size of the leak.

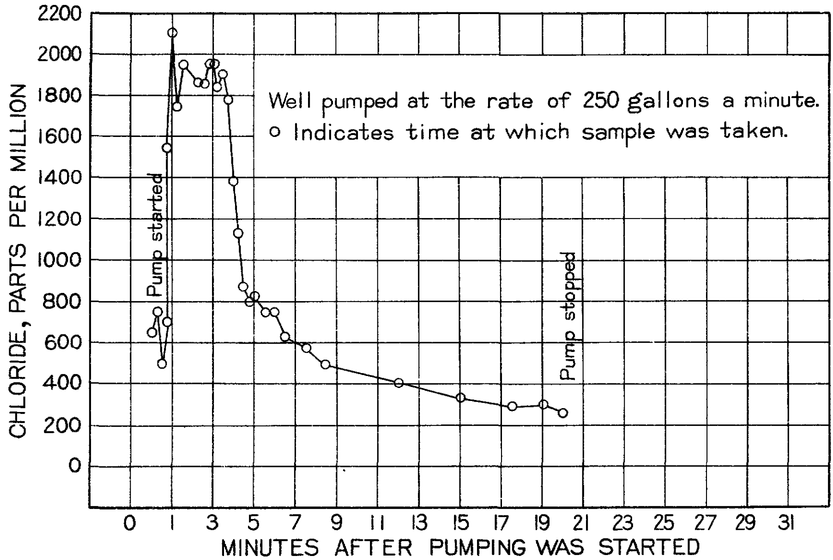


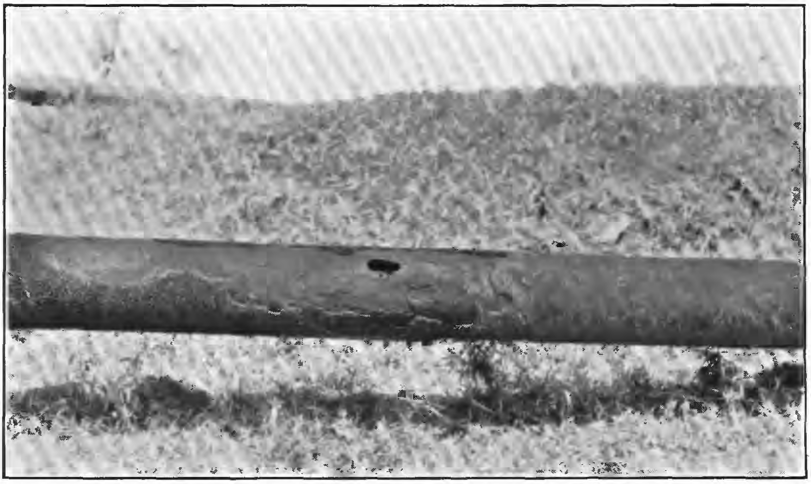
Figure 1.--Diagram showing fluctuations in chloride content of water pumped from the Pickna well in the Winter Garden area, Texas.

A typical time-salinity curve showing the chloride content of samples of water obtained during a pumping test of a well belonging to J. Pickna, 4 miles east of Winter Haven, is shown in figure 1. The well was drilled in 1912 and has 1,070 feet of 8-inch casing. The graph shows that the water discharged by the pump during the first three-quarters of a minute averaged about 700 parts per million of chloride. Toward the end of the first minute the chloride suddenly increased to 2,100 parts per million, then dropped to an average of about 1,900 parts per million for the next 3 minutes. During the fifth minute it dropped to 800 parts, then continued to decline until at the end of 20 minutes it had dropped to 260 parts per million, which was even lower than at the start of the test. The curve indicates that when the pump was shut down prior to the test the well was filled with water of low salinity. While the pump was idle salt water entered the well somewhere near the top and, being heavier, settled down into and displaced the fresh water; the salt water not only reached all parts of the well below the point at which it entered but also migrated into some of the fresh-water sand around the well. When the pump was started the comparatively fresh water in the well above the leak was discharged first, and as the whole column of water in the well moved upward the pump picked up the salt water and finally the fresh water from the bottom. Had pumping continued the salt content would probably have continued to decrease very slowly for some time. The test shows very definitely the presence of a leak in the casing in the upper part of the well, but not the exact depth of the defect.

Pumping tests were made on a well belonging to the Bassett ranch, 1½ miles southeast of Carrizo Springs, Tex. The well was drilled in 1924 and has 480 feet of 10-inch casing. Plate 1, A, shows one of three holes in a 20-foot piece of pump column that was removed from the well. The entire 20-foot piece was badly corroded and several depressions in it would soon have developed into additional holes. The pumping tests on this well showed progressive changes in the chloride content of the water similar to those in the Pickna well, described above, and tests with the electrical apparatus showed that salt water was entering the well through holes in the well casing opposite to those in the pump column.

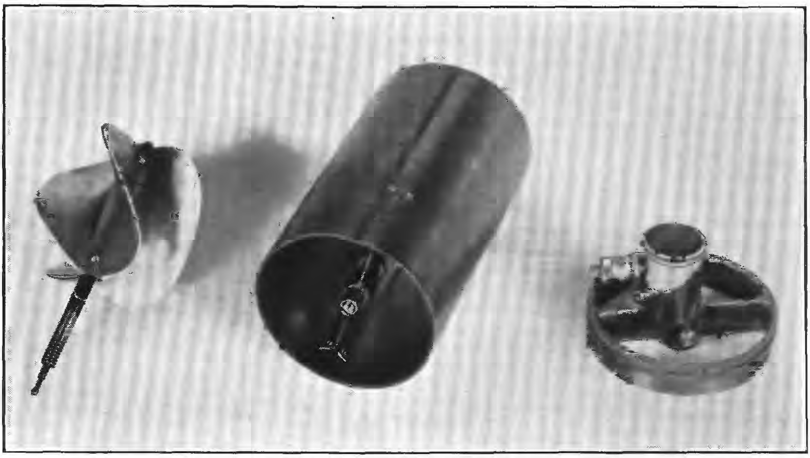
After a defective well has been repaired the pumping method can be used to determine whether the leak has been stopped, as in a well belonging to O. Pollard, 6½ miles southeast of Carrizo Springs, Tex. The well was drilled in 1927 and was repaired in the winter of 1929-30; it is 677 feet deep and has 10-inch casing. Plate 1, B, shows two holes in a piece of defective casing that was removed from the well. The holes had an area of about 6 square inches and were near the end of a joint of casing, just above the coupling, at a depth of 212 feet. After the new casing was installed the well was pumped and the water tested at intervals over a period of more than 2 months. Figure 2 shows the time-salinity curve compiled from the results of the tests during periods of pumping aggregating 118 hours.

The pump was again started after the completion of the repairs and 6 hours later the water contained about 3,800 parts per million of chloride.



A. SECTION OF A PUMP COLUMN SHOWING THE EFFECT OF CORROSION BY SALT WATER.

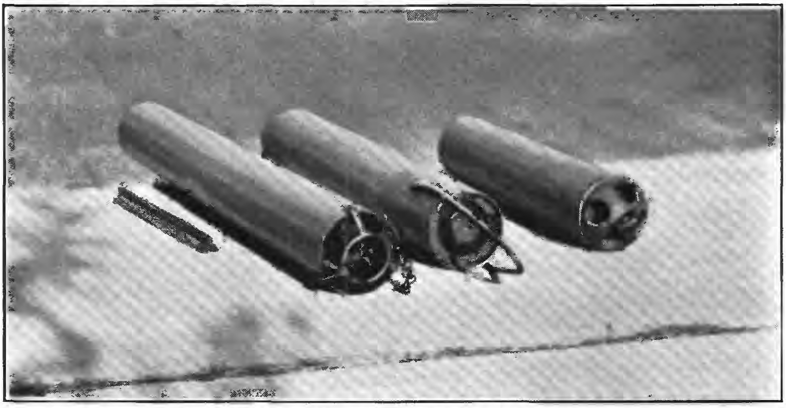
B. WELL CASING SHOWING HOLES MADE BY SALT WATER.



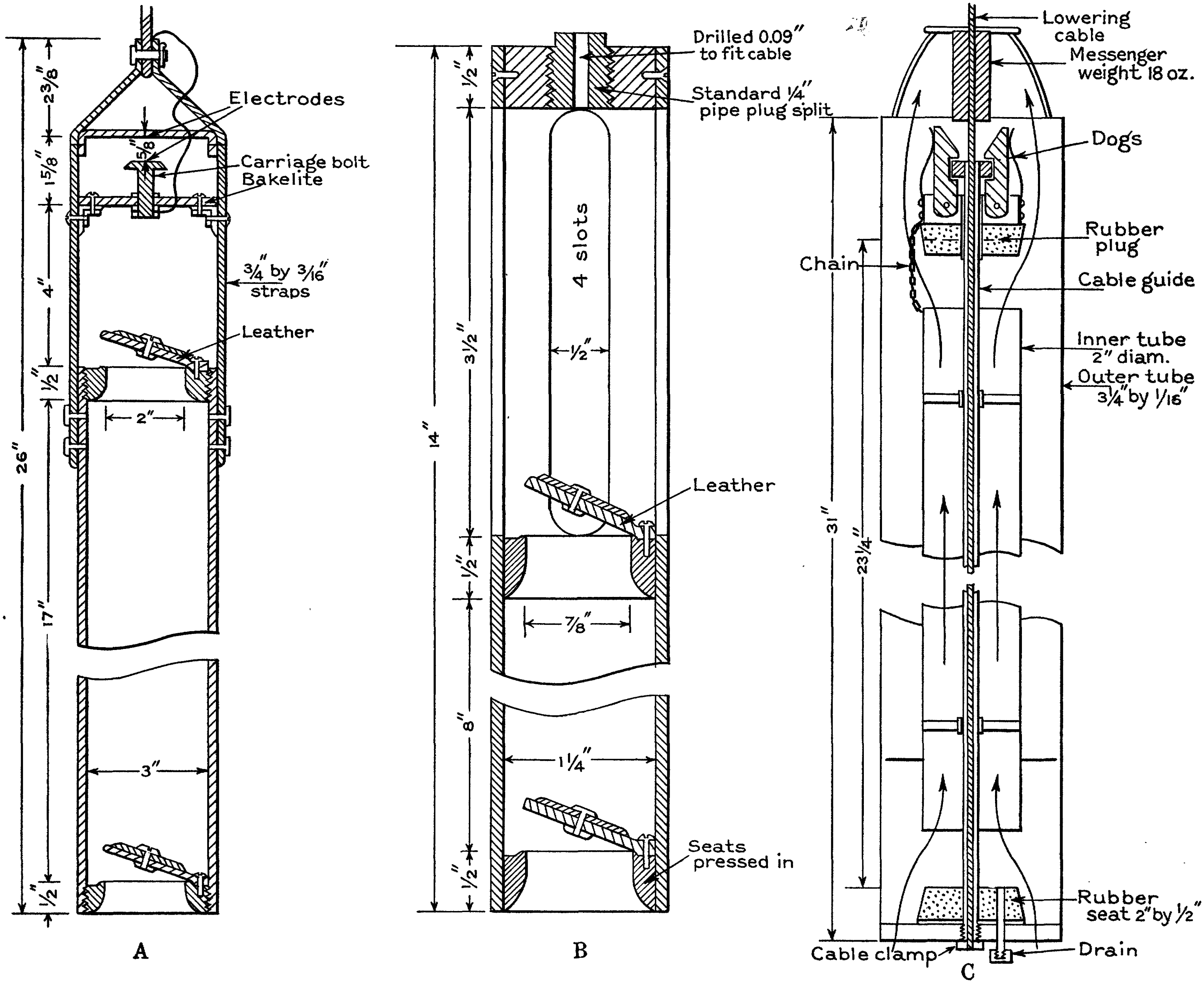
A. DEEP-WELL CURRENT METER.

B. POWER-DRIVEN WINCH USED FOR LOWERING AND RAISING EQUIPMENT IN WELLS.

A. DEEP-WELL WATER SAMPLER WITH ELECTRODES USED IN WINTER GARDEN AREA, TEX.



B. DEEP-WELL WATER SAMPLERS USED IN SARASOTA COUNTY, FLA.



CROSS SECTIONS OF DEEP-WELL WATER SAMPLERS.

A, Water sampler used in Winter Garden area, Tex.; *B*, Water sampler used in Kleberg County, Tex.; *C*, Water sampler used in Sarasota County, Fla.

At the end of 118 hours of pumping the salinity had been reduced to 130 parts per million, which was close to the average for the locality. The curve indicates that the water-bearing sands supplying the well were filled with salt water for some distance around the well, but as pumping

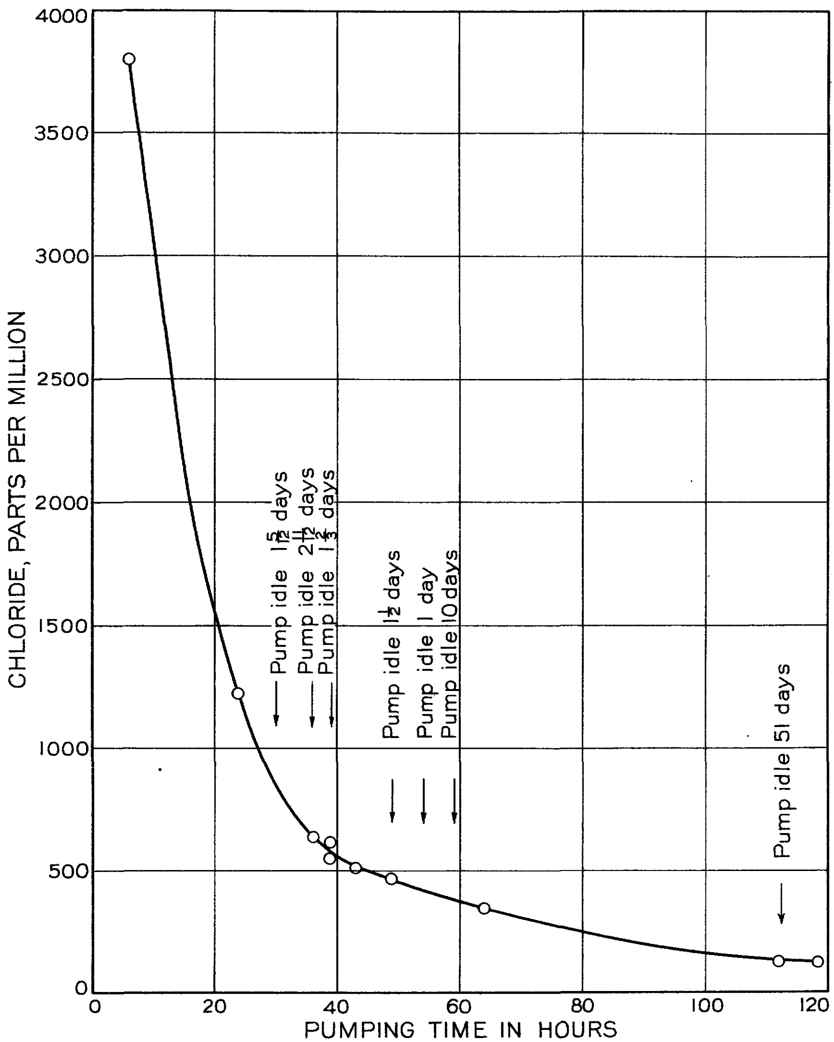


Figure 2.--Diagram showing fluctuations in chloride content of water pumped from the Pollard well after the well had been repaired.

progressed fresh water was gradually drawn toward the well and displaced the salt water. The salt content of the water decreased as pumping proceeded and did not rise noticeably at any time, even though the pumping was not continuous; therefore it was evident that the repairs were satisfactory.

Velocity method

According to Meinzer[6] the velocity or current-meter method of exploring wells was used by W. G. Sloan, of the United States Department of Agriculture, and W. B. Heroy, of the United States Geological Survey, in connection with drainage investigations on the Twin Falls South Side project, in Idaho, from 1910 to 1914.[6] The exploration of wells with a current meter in Honolulu, Hawaii, and near Roswell, N. Mex., for the purpose of determining the location of underground leaks that were wasting artesian water has been described by McCombs and Fiedler.[7] The artesian head in the water-bearing formations tapped by the wells in both of these areas was relatively high, and the leakage was normally from the well into a formation containing water under a lower head. The location of the leaks was established by lowering the meter into the well and determining the places above the main water-bearing formation at which there was a change in the rate of upward movement.

The following description of the deep-well current meter, the essential parts of which are shown in Plate 2, A, is quoted from the report by Fiedler[8] on the use of this equipment in the Roswell artesian basin.

> The Au deep-well current meter is essentially a turbine wheel mounted within a cylindrical brass case, which is suspended in a 3-inch pipe and is lowered into the well and removed from the well by means of a cable and reel. Near the lower end of the brass meter case, on the inside, is mounted a pointed bearing upon which the wheel revolves. This pointed bearing is provided with a movable nut which is turned up when the meter is not in use, thereby removing the turbine wheel from the bearing and preventing it from being damaged. At the upper end of the brass cylinder there is a movable frame which supports a single or a pentapoint commutator head like those used in the Price current meter. These commutator heads are interchangeable, and either may be used according to the velocity of the water in the well. The vanes of the turbine are made of aluminum. The lower bearing of the wheel is a pivot cup of hard steel, and the upper shaft is made of unhardened tool steel. The upper shaft is drilled and tapped to accommodate the standard Price cam and worm screw to be used with the single and pentapoint heads, respectively.

Before being taken to the field the meter was rated to determine the relation between the velocity of the water and various speeds of the turbine wheel, and a rating table was compiled. The meter is lowered into and raised from the well by means of a cable and a winch mounted on a

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6/ Meinzer, O. E., Outline of methods for estimating ground-water supplies: U. S. Geol. Survey Water-Supply Paper 638, p. 125, 1932.

7/ McCombs, John, and Fiedler, A. G., Methods of exploring and repairing leaky artesian wells: U. S. Geol. Survey Water-Supply Paper 596, pp. 1-32, 1927.

8/ McCombs, John, and Fiedler, A. G., op. cit., pp. 25-26.

truck and driven by a belt attached to a wheel of the truck. (See pl. 2, B.) The cable passes over a wheel with a counter that indicates at any time the depth of the meter in the well. The cable has a diameter of seven thirty-seconds of an inch and is composed of six strands of seven wires each of galvanized aircraft wire, wound around an insulated core of seven no. 28 annealed copper wires. The meter is electrically connected with the surface equipment, a circuit being established by means of a dry cell, the double conductor cable, and a set of earphones worn by the observer. At each revolution of the turbine wheel the circuit is closed and opened in the commutator head of the meter, causing a click in the earphones. The velocity of the water at any point in a well may be readily determined by timing with a stop watch the clicks registered in the earphones and applying the rating table.

An extensivs series of tests[9] was made in 1933 and 1934 in the hydraulic laboratory of the National Bureau of Standards to rate and determine the operating characteristics of the deep-well current meter, especially with respect to the action of the meter in a well near a leak or a change in the size of casing. These tests, which simulated field conditions as closely as possible, covered a wide range of flows in casings from 3 to 12 inches in diameter.

In the greater part of the Winter Garden area of Texas formations containing salt water lie above the fresh-water formation, and the salt water enters the wells during periods when the head of the fresh water is low. It was therefore reasoned that the entrance of salt water into the well should be accompanied by movement of water in the well in the vicinity of the leak and that the deep-well current meter might indicate this movement. Equipment of the same type as that used in the Roswell area was therefore tried out in the study of the salty wells in Texas. Considerable difficulty was experienced in introducing the current meter into the wells because of the presence of pumping equipment or other obstructions, but during July and August 1930 meter explorations were successfully carried out in 23 wells, most of which were known to be contaminated to some extent with salt water. In none of them, however, was a movement of water encountered sufficient to turn the meter. As the tests were made at a time of the year when the head of the fresh water

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9/ Report on investigation of deep-well current meters for water-resources branch, U. S. Geological Survey: Nat. Bur. Standards unpublished report, pp. 1-76, 1934.

was at its highest, it is probable that there was very little difference between the head of the salt water and that of the fresh water. Although the information obtained was negative in character, it was believed to be sufficient to warrant the conclusion that the underground leakage of water from defective wells or into defective wells was not very great at the time the explorations were made.

In Sarasota County, Fla., also, the tests with the meter indicated that no great amount of leakage was taking place in the wells that were examined. In some of the flowing wells in that area the meter showed that the water in the bottom 100 to 200 feet of the wells was not moving. This suggests that the wells had been drilled deeper than was necessary.

Sampler method

In the sampler method of locating salt-water leaks a container is lowered into the well, and samples are obtained at any depth desired. For work in the Winter Garden area a sampler was assembled consisting essentially of an 18-inch length of 3-inch galvanized pipe provided with a leather flap valve at the top and the bottom. (See pl. 3, A, and 4, A.) This sampler was lowered to the desired depth with the cable and winch used in the explorations with the current meter. Then the cable was given a few short pulls by hand so as to cause the sampler to move up and down rapidly through a distance of about a foot. Experiments showed that the water in the sampler was completely changed in about 10 such up-and-down movements, but in the sampling operations about 75 pulls were given to insure thorough flushing. In removing the sampler from the well care had to be exercised to insure that it moved continuously upward. If a reversal in the movement took place the valves opened and the water was lost.

Among the wells tested with the sampler in the Winter Garden area was one belonging to E. C. Smith, 8 miles southwest of Catarina. The chloride content of the samples obtained from the well plotted against the depth at which the samples were taken indicates that water containing about 6,000 parts per million of chloride was entering the well at a depth of about 180 feet. (See fig. 3 A.)

For work in Kleberg County, Tex., it was desirable to have a small sampler that could be handled with the light portable electrical equipment. A sampler of the flap-valve type using a 1¼-inch pipe about 14 inches long proved very satisfactory for this investigation. (See pl. 4, B.) The sampler is clamped to the supporting cable by means of a 1/8-inch pipe plug that has been drilled to the size of the cable (0.09 inch) and split. With this arrangement the sampler can be removed or attached at will and without disturbing the electrodes.

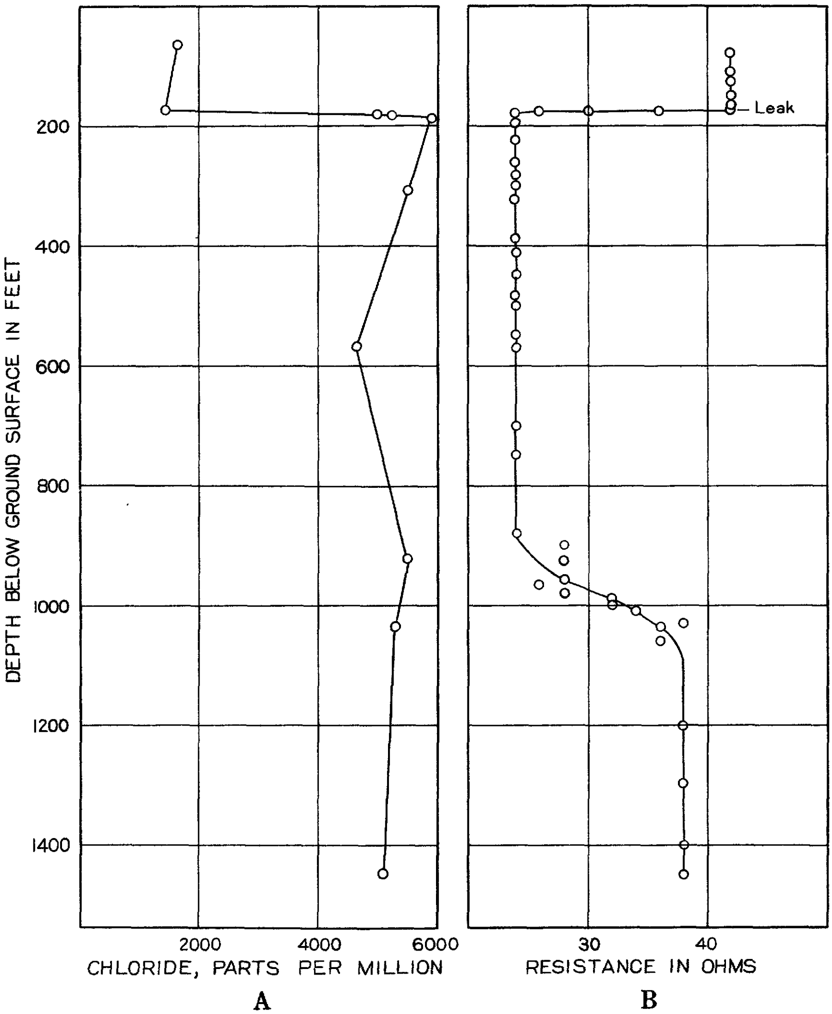


Figure 3.--A, Chloride content (parts per million) of samples brought up by the deep-well sampler from the E. C. Smith well near Catarina, Tex.; B, Resistance of the water at different depths in the E. C. Smith well as indicated by the Wheatstone bridge.

The flap-valve type of sampler is satisfactory for nonflowing wells and perhaps for wells having a small flow but is not adapted to wells that have a strong flow. A special water sampler was designed for wells of large flow and used in Sarasota County, Fla. A view of it is shown at the left in plate 3, B, and a cross section in plate 4, C. It consists of two brass cylinders, an outer one 3 1/8 inches in diameter and an inner one 2 inches in diameter. The cable is securely fastened to the bottom of the outer cylinder by means of a spider connection and cable clamp and passes through a tube at the center of the inner cylinder. The inner cylinder is free to slide up and down the cable a distance of a few inches. When lowered into a flowing well the sampler is in the open position shown in plate 4, C. In this position the rubber stopper above the cylinder is held in place by dogs that are hooked over the top of the guide tube, and the inner cylinder is held up by a small chain attached to the stopper, thus allowing the water to flow freely through the apparatus. When a water sample is desired, a messenger weight is sent down the cable to unhook the dogs, permitting the inner cylinder to drop onto the plug at the bottom and also permitting the top stopper to settle down and close the top of the cylinder.

Electrical-conductivity method

The principle of determining the salinity of water by measuring its electrical conductivity has been applied in connection with the determination of soluble salts in soils by the United States Department of Agriculture[10/] and also in connection with the measurement of the salinity of sea water by the United States Coast Guard.[11/] Slichter[12/] applied this

10/ Whitney, Milton, and Means, T. H., An electrical method of determining the soluble salt content of soils: U. S. Dept. Agr., Div. Soils, Bull. 8, 1897. Briggs, L. J., Electrical instruments for determining the moisture, temperature, and soluble salt content of soils: U. S. Dept. Agr., Div. Soils, Bull. 15, 1899. Davis, R. O. E., and Bryan, Harry, The electrical bridge for the determination of soluble salts in soils: U. S. Dept. Agr., Bur. Soils, Bull. 61, 1910. Davis, R. O. E., The use of the electrolytic bridge for determining soluble salts: U. S. Dept. Agr. Circ. 423, 1937.

11/ International ice observations and ice patrol service, season of 1921: U. S. Coast Guard Bull. 9. Idem, season of 1924: U. S. Coast Guard Bull. 12. Wenner, Frank, Smith, E. H., and Soule, F. M., Apparatus for the determination aboard ship of the salinity of sea water by the electrical-conductivity method: Nat. Bur. Standards Research Paper 223, 1930.

12/ Slichter, C. S., The motions of underground water: U. S. Geol. Survey Water-Supply Paper 67, pp. 48-51, 1902; Description of underflow meter used in measuring the velocity and direction of movement of underground water: U. S. Geol. Survey Water-Supply Paper 110, pp. 17-31, 1905; Field measurements of the rate of movement of underground water: U. S. Geol. Survey Water-Supply Paper 140, pp. 9-85, 1905.

principle in his electrical method of measuring the rate of movement of ground water. Other research workers have studied the relation of the electrical conductivity of solutions to their dissolved solids and have performed many tests. Some of the research work in connection with the conductivity of sea water and the results obtained are briefly discussed by Service.[13/] So far as the writers know this method was first used in determining the location of salt-water leaks in wells in the Winter Garden area of Texas. The method was introduced in that area because the pumping and velocity methods, though providing information of definite value, did not serve to establish within reasonably close limits the location of the salt-water leaks in the wells.

The electrical-conductivity method is based upon the fact that the conductivity of water increases with an increase in the dissolved solids. As the great difference in total dissolved solids between the fresh water and the contaminating water is made up chiefly of chloride salts, an increase in conductivity indicates greater salinity. The procedure, therefore, is to lower two electrodes, or insulated pieces of metal, into a well and to determine the degree of conductivity of the water between them. Considerable experimental work was done with various types of electrodes and electrical measuring apparatus before the equipment described below was assembled. Two sizes of electrode equipment were constructed--a large set mounted in the water-sampler cage, to be used in open wells and handled with the power-driven winch, and a miniature set, to be used in wells in which the pumping equipment is still in place and it is therefore impossible to lower the large set. The electrical measuring devices are of three types--a Wheatstone bridge to measure the resistance of water to current, a Wheatstone bridge to measure the resistance of water to alternating current, and a milliammeter to measure the direct current between the electrodes. A diagram of each of the circuits is shown in plate 6, the Wheatstone bridge used in the Winter Garden area is shown in plate 5, A, and apparatus used in Sarasota County, Fla., is shown in plate 5, B. Although any of these electrical measuring devices will give satisfactory results with either of the electrodes described in this report, the principal arrangement used in each investigation will be discussed.

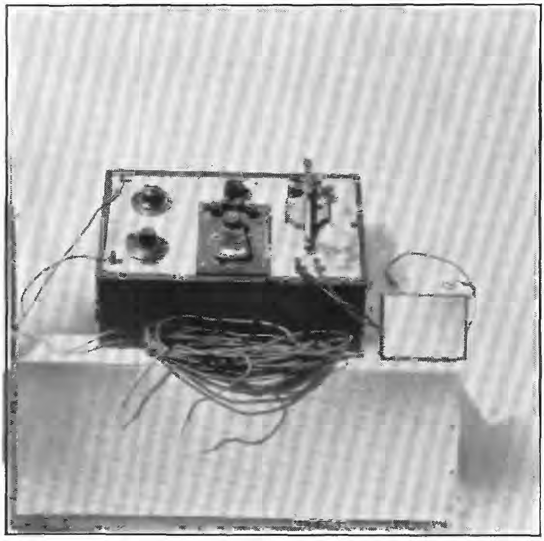
13/ Service, J. H., Measurement of salinity of sea water: U. S. Coast and Geodetic Survey Special Pub. 147, 1928.

Sampler electrodes and Wheatstone bridge

The large set of electrodes and Wheatstone bridge were first used in the Winter Garden area. The apparatus consists of a pair of electrodes mounted on the top of a cage attached to the upper end of the water sampler. (See pls. 3, A, and 4, A.) The upper cross brace of the cage forms one of the electrodes; the other consists of a $\frac{1}{4}$-inch carriage bolt that is held in place and insulated from the frame by means of a strip of bakelite bolted to the sides of the cage. The space between the two electrodes is five-eighths of an inch. The lower electrode is connected to the insulated core of the cable, and the upper one is grounded to the steel strands of the hoisting cable.

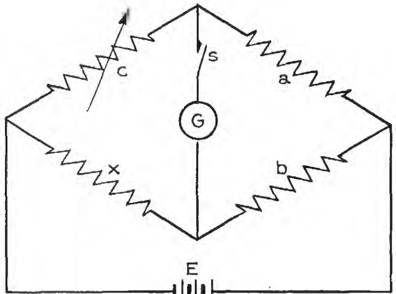
The Wheatstone bridge was constructed chiefly from spare radio and meter-testing parts. The circuit, as shown in plate 6, A, is made up of two fixed resistances of 400 ohms each, a variable resistance having a maximum value of 400 ohms, and the resistance of the water between the electrodes. A radio C battery of $4\frac{1}{2}$ volts is used to supply the current. In operating the equipment the variable resistance is adjusted to keep the galvanometer in the neutral position. The galvanometer is a Leeds & Northrup portable instrument of the wire suspension type. A key switch is used in the meter circuit. Only four connections need to be made in setting up the bridge -- two leads are connected to the cable through the brushes on the hoisting drum and two to the battery, and it is immaterial which way the cable leads are connected.

Tests were made by means of the water sampler equipped with electrodes and the Wheatstone bridge on a well belonging to E. C. Smith, 8 miles southwest of Catarina; this well is 10 inches in diameter and 1,655 feet deep and was drilled in 1928. The chloride content of the samples of water is indicated in figure 3, A, and the electrical conductivity of the water in figure 3, B. The electrical resistance indicated by the apparatus was constant at about 42 ohms from the top of the water column to a depth of about 170 feet below the ground. It dropped suddenly to 24 ohms at a depth of about 180 feet and remained at about that figure to a depth of about 900 feet. The resistance increased steadily below about 900 feet and reached 38 ohms at about 1,100 feet, below which it again remained constant. Both the sampler test and the electrical-conductivity test indicated that salt water was leaking through the casing of this well at a depth of about 180 feet below the ground. Salt water from the

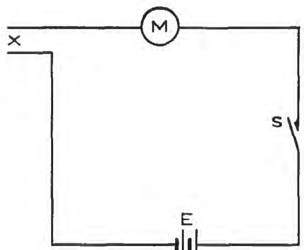


A. WHEATSTONE BRIDGE USED IN WINTER GARDEN AREA, TEX.

B. APPARATUS USED TO EXPLORE WELLS IN SARASOTA COUNTY, FLA.



A



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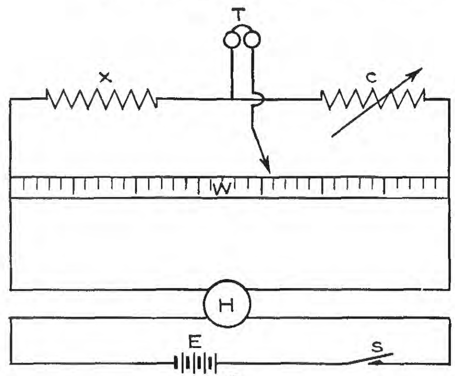
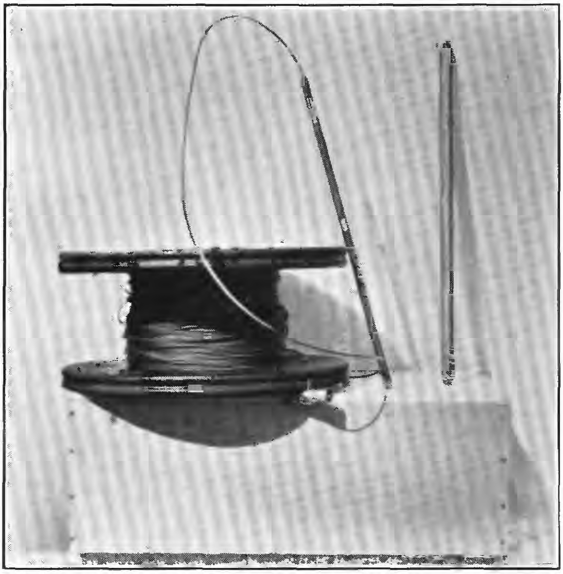


C

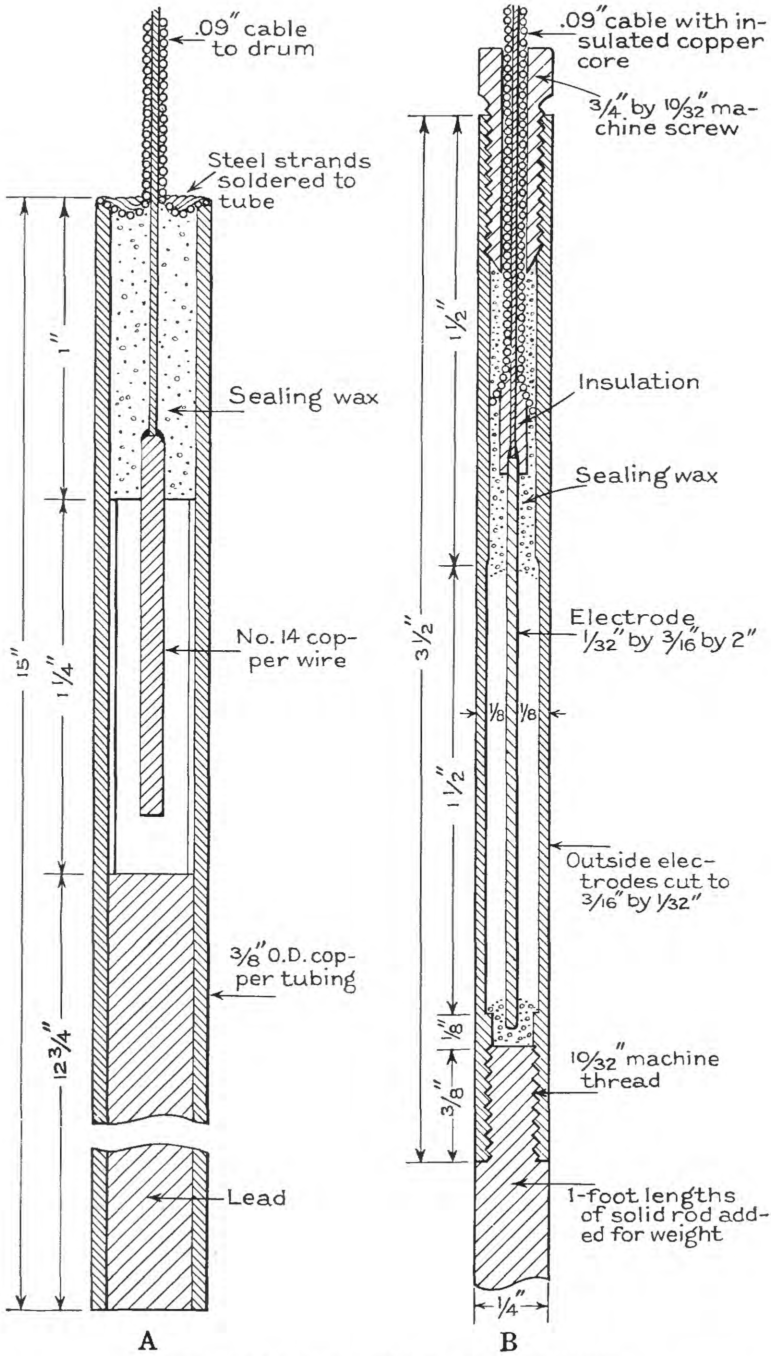
DIAGRAMS OF ELECTRIC CIRCUITS.

A, Wheatstone bridge direct-current electric circuit used in Winter Garden area, Tex.; *B*, Milliammeter direct-current electric circuit used in Kleberg County, Tex.; *C*, Wheatstone bridge alternating-current electric circuit used in Sarasota County, Fla.



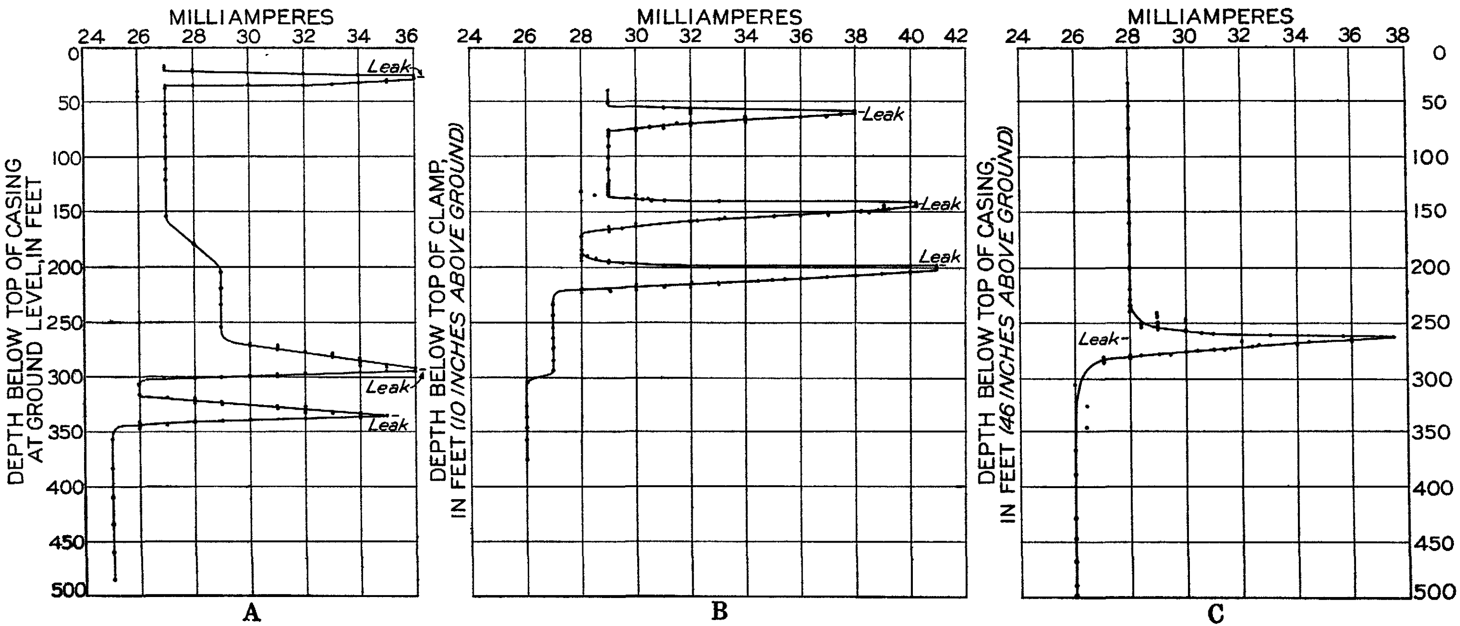
A. EQUIPMENT WITH MINIATURE ELECTRODES USED IN WINTER GARDEN AREA TEX.

B. HAND-OPERATED APPARATUS USED TO EXPLORE WELLS IN KLEBERG COUNTY, TEX.



CROSS SECTIONS OF MINIATURE ELECTRODES.

A, Miniature electrodes used in Winter Garden area, Tex.: *B*, Miniature electrodes used in Kleberg County, Tex., and in Sarasota County, Fla.



DIAGRAMS SHOWING LOCATIONS OF SALT-WATER LEAKS IN WATER WELLS IN KLEBERG COUNTY, TEX., INDICATED BY THE MINIATURE ELECTRODES AND MILLIAMMETER EQUIPMENT.

A, Well of B. Gillespie, 3 miles southwest of Kingsville; *B*, Well of G. Nolan and others, 1 mile west of Kingsville; *C*, Well of Mrs. J. G. Olson, 1 mile southeast of Kingsville.

leak apparently had filled the well below the leak, but in the lower part of the well, opposite the fresh-water sands, there had been some freshening as the result of mixture with fresh water.

Miniature electrodes

Winter Garden area, Tex.- In order to explore wells without removing the pumps a pair of electrodes was made, small enough to be inserted into the well between the casing and pump column. The outfit used in the Winter Garden area (see pls. 7, A, and 8, A) includes a 15-inch length of 3/8-inch copper tubing, at the upper end of which are two 1¼-inch slots opposite each other. This tube is soldered to the outer strands of the cable and constitutes one electrode. The other electrode consists of a piece of no. 14 copper wire, which is fastened with sealing wax in the center of the tube directly opposite the slots and is attached to the insulated core of the cable. The cable has a breaking strength of 450 pounds and consists of six strands, each of seven plow-steel wires 0.009 inch in diameter, wound around a core of twelve B. & S. 36 gage enameled copper wires insulated with four winds of saturated cotton. The cable is wound on a small hand reel.

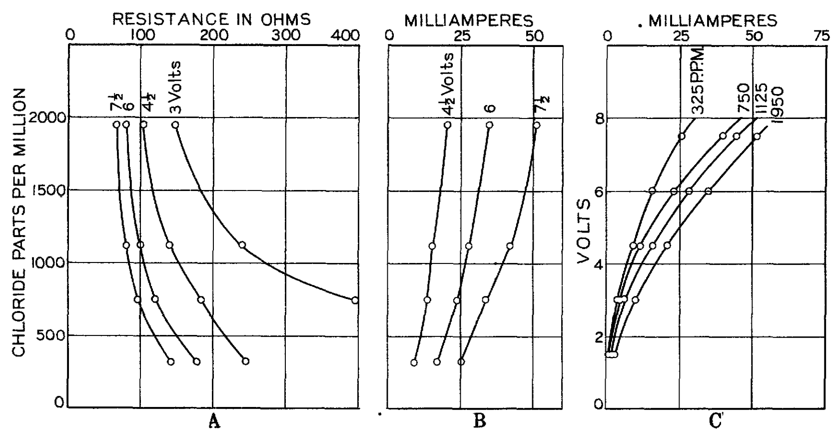


Figure 4.—Diagrams showing the effect of varying the voltage on the resistance and conductivity of saline waters.

To determine the effect of different voltages on the relation between salinity and the resistance of the water a series of preliminary tests was made with this equipment. The electrodes were submerged in water of different salinities, different voltages were applied, and the indicated resistance was noted. The results of the tests are shown in figure 4.

These tests show that with a direct-current voltage of less than 3 volts the Wheatstone bridge is too sensitive in waters low in chloride, indicating resistances that are too great to measure with the apparatus. With more than 3 volts the bridge is less sensitive at all salinities, and as the voltage is increased the point at which an increase in salinity fails to register becomes lower. At low voltages, with the attendant low currents, gas bubbles that form on the negative electrode do not break away freely, and these bubbles increase the resistance. As the voltage is increased gas is formed more rapidly and the bubbles break away freely, and resistance from this cause is partly eliminated. However, 3 volts afforded satisfactory tests when the current was measured instead of the resistance, and this voltage was used in practically all the tests with the milliammeter and the miniature electrodes. The milliammeter (pl. 6, B) was less bulky than the Wheatstone bridge and gave just as satisfactory results.

Figure 5 shows the result of a test made with the miniature electrodes on the Pickna well after the pump had remained idle for 2 hours following the pumping test described on page 5. A shows the current indicated by the milliammeter for different positions of the electrodes in the well; B shows the resistance of the water to direct current as measured by the Wheatstone bridge. The resistance was practically constant from the water surface to a depth of about 212 feet; from 212 to 220 feet it dropped rapidly; from 220 to 225 feet it remained constant; and below 225 feet it gradually increased, reaching the original amount at about 275 feet. It is evident from the graphs that during the 2 hours that the pump was idle salt water leaked into the well at a depth of about 220 feet, completely displacing the fresh water in the casing for a depth of about 5 feet and contaminating it down to a depth of about 300 feet. From the amount of contamination during the period it was estimated that the well was receiving about 1 gallon a minute of highly mineralized water.

Kleberg County, Tex.- For the work in Kleberg County, Tex., a miniature apparatus was assembled that in some ways was an improvement over the one constructed for the Winter Garden area. In this outfit the metal spool is mounted upon a frame and is provided with commutator brushes so that the milliammeter can be kept in the circuit while the electrodes are being lowered into a well. The whole apparatus, exclusive of the wire, weighs less than 5 pounds. A view of the apparatus is shown in plate 7, B. The electrodes are shown in plate 8, B. They consist essentially of a 3½-inch length of ¼-inch brass welding rod that has been drilled through and threaded at each end to accommodate a no. 10 machine screw with 32 threads to the inch. The side walls are cut through on opposite sides to form a slot about one-eighth of an inch wide for a length of about 1½ inches. The lock screw is drilled longitudinally to allow the 0.09-inch cable to pass through and is split at the end so that it serves to pinch the cable and act as a clamp when screwed in beyond the limit of the female threads. The inner insulated core, or electrode, which is a tongue or plate of nickel alloy one thirty-second by three-sixteenths by 2 inches, is insulated from the rod at the top and bottom with sealing wax. With these electrodes the direction of the current makes very little difference, because by using a plate-center electrode instead of a round wire the two electrodes have more nearly the same area of effective surface exposed to the water.

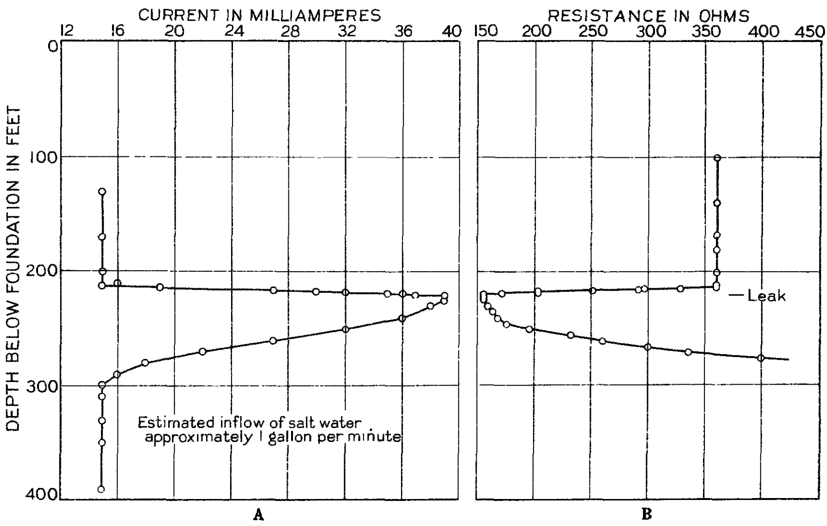


Figure 5.--Diagrams showing the results of explorations with the miniature electrodes in the Pickna well. A, Conductivity indicated by the milliammeter; B, Resistance in ohms indicated by the Wheatstone bridge.

Results of three of the tests in which a milliammeter was used to measure the current are shown in plate 9. All the tests were made in wells that had been pumped nearly fresh a few minutes before the tests. These diagrams show that there were three leaks in two of the wells and one leak in the other. If the wells with more than one leak had stood idle for several days before the tests were made only the top leak could have been located, because the wells would have been filled with salt water from this leak to the bottom.

Sarasota County, Fla.- The electrodes used during the investigation in Sarasota County, Fla., were similar to those used in Kleberg County.

Although the practicability of using the Wheatstone bridge with direct current was demonstrated in the exploration of the wells in the Winter Garden area of Texas, it was decided that experiments should be made with the alternating current especially to study the effect of polarization. A new apparatus was assembled that includes a bridge with a slide wire of a resistance of 0 to 100 ohms, resistances capable of registering from 1 to 9,999 ohms, and a high-frequency hummer. In this apparatus the hummer is operated by four standard dry cells and supplies alternating current of 1,000 cycles. The operation of the equipment is essentially the same as when the direct current is used, except that the circuit is balanced by adjusting the rheostat and slide wire until the minimum hum is obtained in a set of ear phones. This apparatus was used by Stringfield and Fiedler in Florida during 1932 and is illustrated in plates 5, B, and 6, C. Tests thus far have not shown that the alternating current has any special advantage over the direct current in the leakage explorations.

Additional characteristics

Much could be written about the effect of passing an electrical current through water containing a large amount of salt. The subject is discussed in most books on chemistry. It is known that counter currents are set up in the solution, but the effect of these currents upon the readings of the milliammeter or Wheatstone bridge is small, and it is believed they need not be taken into consideration when the electrodes are used under the conditions described in this report.

It is important to bear in mind when building the conductivity apparatus or making a test of a well that complete insulation in the wiring system and the electrodes is absolutely necessary. If the insulation of the inner core of the cable breaks down, it is generally almost impossible to make satisfactory repairs in the field. The insulation must be water tight, otherwise the current will leak through to the outer grounded strands instead of following the route of greater resistance between the electrodes. Care must be taken to insure that the readings obtained indicate the salinity of the water at the electrodes rather than at a break in the insulation of the cable many feet from the electrodes. In case a short circuit should occur in the apparatus the milliammeter is less likely to be damaged if a low voltage is being used.

Two ordinary flashlight batteries will furnish current for a dozen or more tests with the miniature apparatus. For tests with the large electrodes three batteries will give the best results. Time is saved and more reliable information obtained if the circuit is closed during the test and the apparatus is lowered slowly and steadily into the well. If pumping equipment is in place it is always advisable to pump the well enough to freshen the water; the casing may have more than one hole in it, and only the top hole can be located if the well has not been pumped.

Summary of results with the electrical-conductivity method

The equipment for detecting contamination by salt water was used in exploring 21 wells in the Winter Garden area of Texas. Of the 16 found to be salty, 10 showed salt water entering at depths ranging from 210 to 250 feet below the ground surface; this is approximately the depth at which the well casing is usually reduced in size and seems to indicate that most of the salt water enters the wells where the casings overlap.

In Kleberg County, Tex., tests were made of 9 wells, of which several showed more than one leak.

In Sarasota County, Fla., tests were made of 12 flowing wells and 1 nonflowing well. The tests with the electrical apparatus indicated that there was no appreciable difference in the concentration of mineral matter dissolved in the water at different depths. Analyses of water samples collected from these wells with the deep-well sampler substantiated the results.

CONSTRUCTION OF WELLS TO AVOID CONTAMINATION BY SALT WATER

Wells that penetrate formations containing salt water are likely to give trouble. The salt water may enter the well where the casing overlaps if the overlap has not been properly sealed or through holes in the casing produced by salt-water corrosion. Much of this trouble can be avoided by proper construction. The well should be cased with a good grade of genuine wrought iron, or cast iron. Reductions in the size of the casing should be as few as practicable. Where reductions cannot be avoided swaged nipples are preferable to overlapping and the use of lead seals to close the annular space at the overlap. The casing should be as well protected as possible to resist corrosion. It is advisable to set the casing just above the fresh-water formation and concrete the lower half of the bottom length while the hole is full of mud, thus leaving a wall of mud on the outside to keep the salt water away from the casing. It is a good plan to paint the casing with asphaltic paint and wrap it with canvas or heavy paper to protect the asphalt from scratches while the string is being lowered into the well.

It costs much less to take extra precautions against salt water when the well is being drilled than it does to repair a well after it becomes contaminated with salt water. If only a cable-tool well-drilling rig is available a well that has become contaminated can be repaired by inserting a string of new casing on the inside of the old one. If a rotary drilling rig is available a new casing can be rotated around the old one, and the old one can then be removed from the hole. In some wells that are not likely to cave in it is possible to pull the old casing and insert a new one. New casing inserted inside of old casing cannot be expected to last more than a few years. If the defective casing is pulled a longer life can be expected of the new casing if special precautions are taken to leave a wall of mud on the outside to protect it.

The data thus far obtained in Kleberg County and in the Winter Garden area appear to indicate that the salt water contamination is not yet serious except as it affects individual wells. But salt water is now entering the fresh-water formations through these defective wells and if allowed to continue may eventually cause serious general contamination. In order to avoid this result it is suggested that all old wells no longer in use be sealed from bottom to top. This can be done by cleaning out the well and pumping in neat cement or thick gritless clay, beginning at the bottom and continuing until the well is filled all the way to the surface. No attempt should be made to seal a well by simply shoveling dirt or debris in at the top; if this is done the filling material probably will bridge at some point above the bottom of the well, and although the well may appear to be sealed at the top, there will still be an open hole below, through which contamination can enter.

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