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THE ARTESIAN WATER SUPPLY OF THE DAKOTA SANDSTONE IN NORTH DAKOTA, WITH SPECIAL REFERENCE TO THE EDGELEY QUADRANGLE.

By Oscar E. Meinzer and Herbert A. Hard

INTRODUCTION.

The Dakota sandstone and the overlying dense plastic shales form the most remarkable artesian basin in the United States with respect to its great extent, the long distances through which its water has percolated from the outcrops of the sandstone in the western mountains to the areas of artesian flow, and especially the tremendous pressure under which the water in the sandstone was originally held by its thick and continuous cover of impermeable shales. In 1882 a well was drilled to the Dakota sandstone at Aberdeen, S. Dak., by the Chicago, Milwaukee & St. Paul Railway Co. This well was reported by Nettleton [1] to have been "the first bore put down which reached the artesian basin of the Dakotas." In 1896 Darton [2] estimated that about 400 artesian wells had been drilled to the Dakota sandstone, presumably in South Dakota and adjacent parts of the artesian basin in North Dakota which he investigated.[3] The strongest of these wells had pressures ranging from 100 to more than 200 pounds to the square inch and flows ranging from 1,000 to more than 4,000 gallons a minute.

The discovery of this remarkable artesian basin naturally caused much excitement and gave rise to extravagant theories as to the quantity of artesian water available and the extent to which it could be used for power and irrigation. The water from the famous well at Woonsocket, S. Dak., was jetted to a height of more than 100 feet and must have produced a spectacle comparable to that of Old Faithful Geyser in Yellowstone National Park (Pl. VI). Many of the wells yielded considerable gas, which must have heightened the spectacular effect with which the water was discharged. On account of the great pressure it was very difficult to finish the wells, and

[1] Nettleton, E. S., Artesian and underflow investigation: 52d Cong., 1st sess., S. Ex. Doc. 41, pt. 2, p. 46, 1892.

[2] Darton, N. H., Preliminary report on artesian waters of a portion of the Dakotas: U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, p. 609, 1896.

[3] Idem, pl. 69.

occasionally a well would get out of control, throw up immense quantities of sand and other material, cause the caving of adjacent land, and, in short, perform in a most sensational manner.

It is exceedingly interesting and gratifying to note that in March, 1890, when the excitement over the artesian wells must have been about at its maximum, Maj. J. W. Powell, Director of the United States Geological Survey,[4] made a statement on the subject before the Committee on Irrigation of the House of Representatives which must have seemed unduly conservative at that time but which clearly indicated the temporary character of the high pressures and discharges and gave an estimate of permanent yield that appears remarkably accurate after 34 years of artesian development and decline. In the summary of his statement appear the following conclusions:

It has been shown that the supply of water to be obtained through artesian wells is narrowly limited, the limitation arising from natural conditions of reception by reservoirs [water-bearing formations], transmission through them, and leakage from them and being expressed practically through the interference of wells one with another. The permanent flow is in some cases much less than the initial flow. * * * While the Dakota sandstone is one of the most important of the known artesian reservoirs, the amount of land which can be redeemed to agriculture through its aid is yet so small that disastrous results might follow if great expectations were aroused in regard to it.

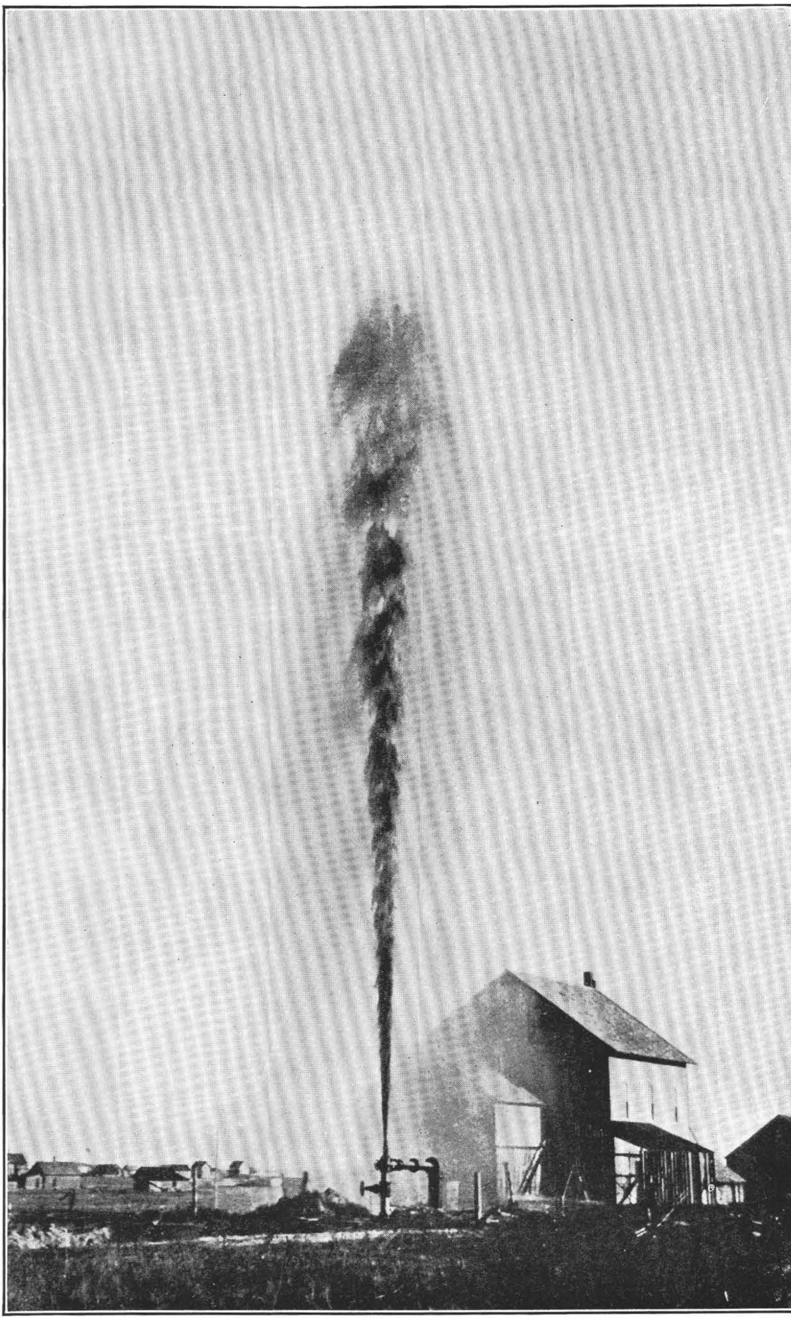
It is estimated that if all the water received by the Dakota sandstone could be brought to the surface by artesian wells, it would cover to the depth of 1 foot an area of land equivalent, at the utmost, to a belt one-fifth of a mile wide and extending from the Canadian boundary to the Mexican.

This is the outside limit for permanent flow. The temporary flow may be large but can not be estimated from existing data. Such is the complexity of conditions and so great is the danger of disaster through expensive exploitation in ignorance of the true conditions that the subject demands the most skillful investigation which can be bestowed.

In 1890 and 1891 an investigation of the artesian basin was made by the United States Department of Agriculture, and the report prepared by E. S. Nettleton, already cited, contains a large number of specific data on individual wells, which are of great value as a record of conditions in the early part of the period of artesian development.

In the ensuing years extensive and somewhat detailed investigations of the geology and hydrology of the artesian basin were made by the United States Geological Survey, the work being done under the direction of N. H. Darton, and numerous reports on the subject were published. Most of these reports relate to areas in South Dakota, which contains the most productive part of the area of

[4] Artesian irrigation on the Great Plains: U. S. Geol. Survey Eleventh Ann. Rept., pt. 2, pp. 260–276, 1891.



ARTESIAN WELL AT WOONSOCKET, S. DAK., ABOUT 1895

The original pressure (1890) was reported to be 250 pounds to the square inch. In 1892 the pressure was reported to be 130 pounds and the flow 1,150 gallons a minute. By 1915 the pressure at Woonsocket had declined to 45 pounds, and by 1923 to 35 pounds. Photograph by N. H. Darton

artesian flow,[5] but some reports covered parts of the artesian basin that lie in other States, including North Dakota.[6]

It is now evident that the decline in artesian head began when the first wells punctured the confining beds and that it has progressed steadily. During the first decade or two of artesian development, however, the head was still so large that not much attention was paid to the obvious symptoms of decline, and it was customary to ascribe notable decreases in head and flow to mechanical difficulties in individual wells. Doubtless considerable decline had already taken place at the time of Nettleton's survey in 1890 and 1891.

Many of the early wells were several inches in diameter, but in later years wells of small diameter came into extensive use. They had two great advantages—they were much less expensive than the larger wells and they could be finished with much less difficulty and less danger of getting out of control. Near the end of the last century and in the first decade of the present century thousands of wells 1¼ or 1½ inches in diameter were drilled to the Dakota sandstone, and eventually artesian wells were to be found on a large proportion of the prosperous farms. In 1915 there were said to be about 10,000 artesian wells in South Dakota,[7] and in 1923 it was estimated that there were between 6,000 and 8,000 artesian wells in North Dakota.[8] During and after the period of active drilling the artesian head dropped rapidly.

In 1914 and 1915 a survey of the geology and artesian conditions of the Edgeley and La Moure quadrangles, N. Dak., was made for the United States Geological Survey by Herbert A. Hard. In 1915 a survey of artesian pressures and flows in South Dakota was made by Homer M. Derr,[9] State engineer of South Dakota. Both investigations showed that the artesian pressure had largely been dissipated and that many of the wells had already ceased to flow. Both Hard and Derr warned against the further waste of artesian water and made correct predictions as to the further decline of artesian head and flow.

In order to obtain definite data as to the rate at which the artesian head and flow are declining, the Edgeley quadrangle, which includes

[5] The following publications of the United States Geological Survey relate to artesian water in South Dakota: Eleventh Ann. Rept., pt. 2; Seventeenth Ann. Rept., pt. 2; Twenty-first Ann. Rept., pt. 4; Prof. Papers 32, 65; Geol. Folios 85, 96, 97, 99, 100, 107, 108, 113, 114, 128, 156, 164, and 165; Water-Supply Papers 34, 90, 227, 428.

[6] The following publications of the United States Geological Survey relate to artesian water in North Dakota: Eleventh Ann. Rept., pt. 2; Seventeenth Ann. Rept., pt. 2; Mon. 25; Geol. Folios 117 and 168.

[7] Derr, H. M., Report on artesian wells: South Dakota State Engineer Sixth Bienn. Rept., for 1915–16, p. 145.

[8] Hard, H. A., Artesian wells of North Dakota: Report to the Governor of North Dakota on flood control for 1919–20, p. 7 [1923].

[9] Derr, H. M., op. cit., pp. 143–282.

the towns of Edgeley, Monango, and Ellendale (fig. 7 and Pl. VII), was resurveyed in 1919 and 1920 by Mr. Hard, who was at that time chief engineer of the State Flood Control Commission. Mr. Hard also made investigations of artesian conditions in other parts of North Dakota. For a number of years the artesian and other ground waters of the entire State have been under investigation by Howard E. Simpson, of the North Dakota Geological Survey. In this project the United States Geological Survey has cooperated with the State Geological Survey.

As a result of the work of Hard and Simpson, and largely through the influence of the North Dakota Well Drillers Association, a law was enacted by the State of North Dakota on March 10, 1921,

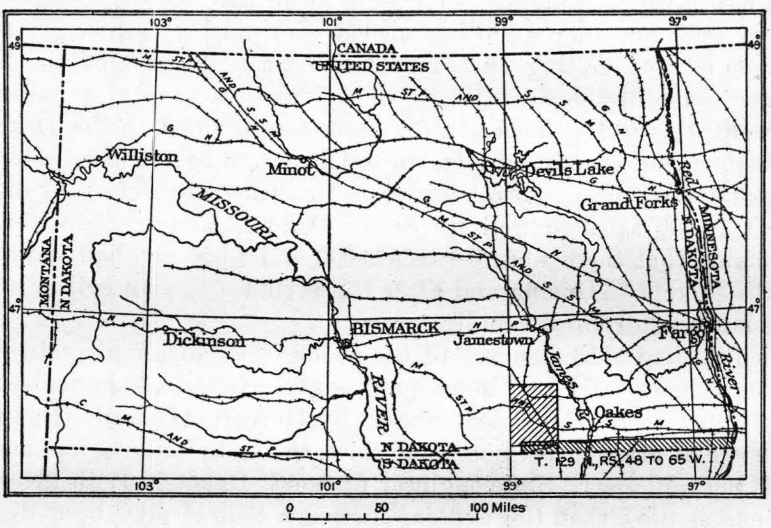


FIGURE 7.—Index map of North Dakota, showing location of Edgeley quadrangle and the row of townships (T. 129 N., Rs. 48–65 W.) on which estimates of artesian-water supply were made.

prohibiting the further waste of artesian water and charging the State geologist or his deputy with the duty of enforcing this law. The State geologist, A. G. Leonard, assigned to Professor Simpson the duty of applying the artesian-water law. Mr. Simpson has given a great deal of serious study to the difficult problems involved in carrying out an effective program of conservation. The annual meeting of the North Dakota Well Drillers Association, held at Grand Forks in February, 1922, was devoted largely to this subject, and in conjunction with this meeting an interstate conference on conservation of the artesian water was held, at which representatives of the North Dakota Geological Survey, the South Dakota Geological Survey, and the United States Geological Survey were present. In 1923 Professor Simpson, with his deputy, C. E. Turnbaugh, began to inspect systematically the artesian wells in the State and to instruct the well owners as to reductions in discharge that should be made.

In order to bring the study in the Edgeley quadrangle up to date a questionnaire covering the present condition of the artesian wells was sent to the owners of wells in or near this quadrangle through the cooperation of the postmasters at Ellendale, Edgeley, Forbes, and Monango. Thanks are due to the postmasters for their helpful cooperation and to the well owners for their hearty response to this questionnaire. In November and December, 1923, through the cooperation of the State Geological Survey, practically all the artesian wells in the quadrangle were examined by Mr. Turnbaugh. This assignment was especially fortunate, because he has been an artesian-well driller in this quadrangle since 1902.

The present brief paper is based chiefly on the data that have been obtained in the successive surveys in regard to about 230 artesian wells in or near the Edgeley quadrangle. A table of these well data is on file in the United States Geological Survey and is to be published in the detailed report on the geology and hydrology of the Edgeley and La Moure quadrangles that has been prepared by Mr. Hard. The well data obtained by Mr. Hard have already been published in a report prepared by him in his capacity as State flood-control engineer.[10]

Mr. Meinzer wishes to express his appreciation to Professor Simpson for his generosity in furnishing essential data obtained in his own field work and to Mr. Hard for his generosity in approving publication of this brief joint report in advance of his detailed report on the Edgeley-La Moure area.

TOPOGRAPHY AND GEOLOGY OF THE EDGELEY QUADRANGLE.[11]

The eastern two-thirds of the Edgeley quadrangle belongs to the so-called James River valley. It is in general a plain that slopes gently toward the east and is underlain by glacial drift, except in a few places where the Pierre shale is exposed. The western third belongs to the Coteau du Missouri—an upland that has a deep cover of glacial drift and an irregular morainal topography. The Coteau stands a few hundred feet above the plain of the James River valley on the east, and in the southern part of the quadrangle it forms a conspicuous escarpment. (See Pl. VII.)

[10] Hard, H. A., op. cit., table opposite p. 96.

[11] Summarized from the unpublished report by Herbert A. Hard.

So far as is known, throughout the quadrangle the drift is underlain by the Pierre shale, below which lie in downward succession the Niobrara shale, the Benton shale, and the Dakota sandstone. On the plain the depth to the Dakota sandstone ranges from about 1,000 to 1,500 feet. On the Coteau the depth is doubtless a few hundred feet greater. The following log was reported for the artesian well drilled at Ellendale in 1886. In this well the glacial drift apparently extends to a depth of 110 feet, where the Pierre shale was presumably struck. The well ends in the Dakota sandstone.

Log of artesian well at Ellendale, N. Dak., drilled in 1886.[a]

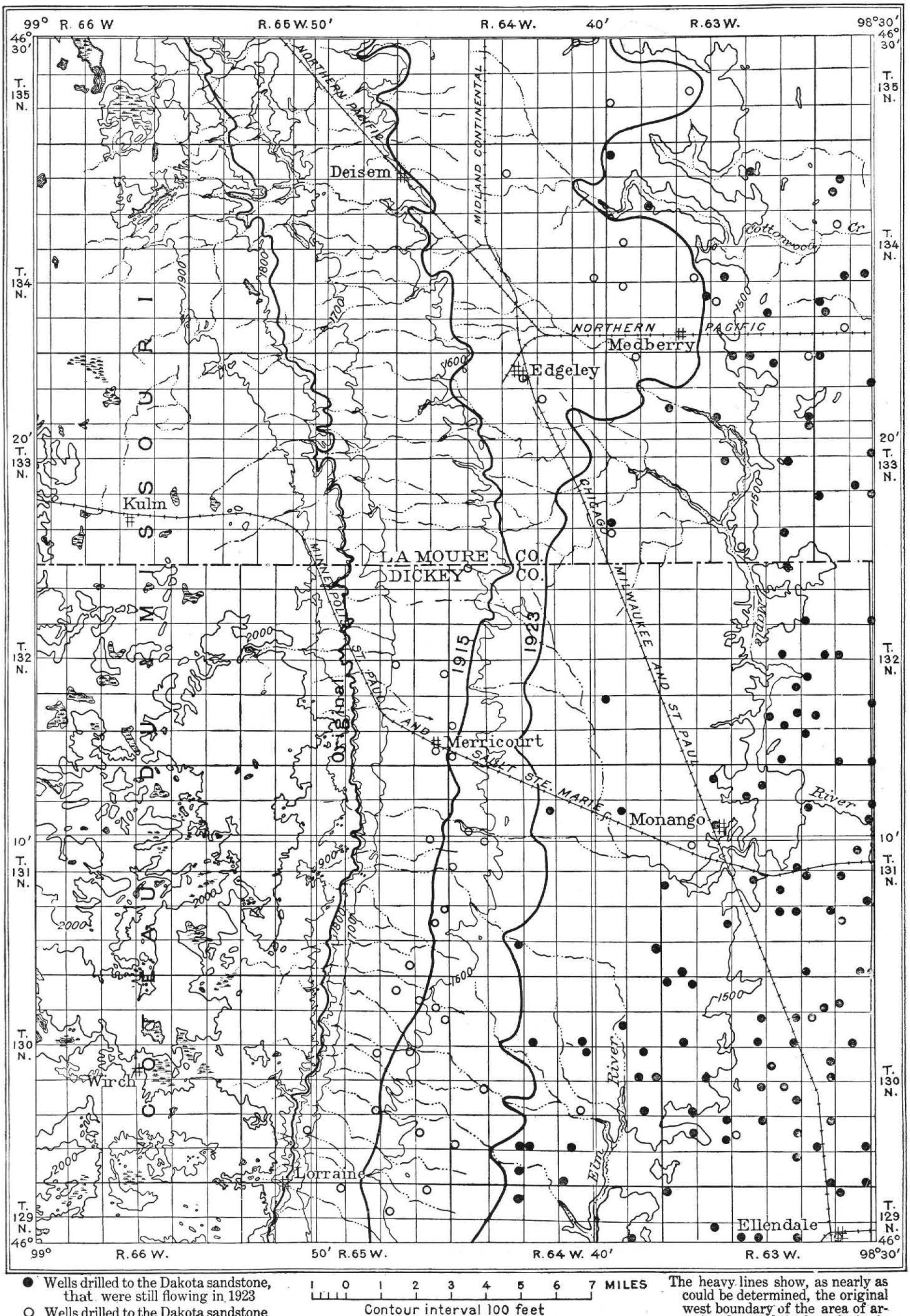
	Thickness.	Depth.
	Feet.	*Feet.*
Yellow clay	25	25
Blue clay	85	110
Shale	925	1,035
Hard sandstone	7	1,042
Soft sandstone	45	1,087

[a] Darton, N. H., U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, pl. 96, 1896.

The following log was reported by George Norbeck, of the Norbeck & Nicholson Co., for the well drilled for the city of Ellendale in November and December, 1923. In this well the glacial drift apparently extends to the depth of 68 feet.

Log of artesian well at Ellendale, N. Dak., drilled in 1923.

	Thickness.	Depth.
	Feet.	*Feet.*
Soil and clay	10	10
Boulders	10	20
Gravel and sand	30	50
Soft blue clay	18	68
Dark sticky shale; thin layer of hard shale at 220 feet	152	220
Dark, nearly black shale	15	235
Firm dark shale	115	350
Hard shale	200	550
Soft dark shale	150	700
Hard grayish shale	20	720
Limestone	25	745
Hard dark shale interspersed with harder layers	75	820
Tough sticky shale	80	900
Shale with traces of sand; thin hard shale at 1,030 feet	130	1,030
Soft gray shale	22	1,052
Sandstone	28	1,080
Gray shale	3	1,083
This is the depth at which the well was completed, but a 3-inch test hole was sunk in search of additional sandstones to a depth of 1,260 feet through formations as follows:		
Gray shale; hard shell 7 inches thick at 1,135 feet	52	1,135
Soft gray shale	55	1,190
Sand	3	1,193
Gray shale	4	1,197
Sand	2	1,199
Gray shale (shading lighter)	61	1,260



● Wells drilled to the Dakota sandstone, that were still flowing in 1923

○ Wells drilled to the Dakota sandstone that originally flowed but had ceased flowing by 1923

1 0 1 2 3 4 5 6 7 MILES

Contour interval 100 feet

The heavy lines show, as nearly as could be determined, the original west boundary of the area of artesian flow and the boundaries in 1915 and 1923

MAP OF THE EDGELEY QUADRANGLE, N. DAK., SHOWING DECLINE IN ARTESIAN HEAD

The Edgeley quadrangle is well adapted for a study of decline in artesian head. Originally the area of artesian flow covered the entire plain and extended high up the escarpment, but apparently it never extended across the Coteau. As the head declined the boundary of the area of artesian flow gradually receded toward the east, but in 1923 it was still in the Edgeley quadrangle. (See Pl. VII.)

ARTESIAN HORIZONS IN THE DAKOTA SANDSTONE.

The artesian well drilled at Ellendale in 1886 is 1,087 feet deep and ends in what is regarded as the upper part of the Dakota sandstone; an artesian well drilled at the same place in 1908 extends to a depth of 1,385 feet and ends in sandstone that is regarded as belonging to the lower part of the Dakota. The sandstone of the upper part does not form a single stratum but rather an indefinite group of sandstone strata and lenses interbedded with shale; the sandstone of the lower part has been reached by so few wells that there is no very definite information as to its thickness and character. However, the upper and the lower sandstones are separated from each other by an effective and widespread confining bed, as is shown by the striking differences in both chemical composition and artesian head of the waters from the two sources.

The upper water is relatively soft, whereas the lower water is extremely hard; moreover, the upper water contains large amounts of common salt and tastes salty, whereas the lower water contains relatively small amounts of common salt but very large quantities of the sulphates. The upper water is generally regarded as less objectionable for household uses than the lower water. It is excellent for laundry and toilet uses and is everywhere used for livestock, but it is too salty to be satisfactory for drinking by man and is injurious to vegetation when used for irrigation. The lower water is very unsatisfactory for laundry and toilet uses or for drinking by man, but it can be used for livestock and is not very injurious when used for irrigation. Prior to the completion of the new well in 1923 both kinds of water were supplied by the city waterworks to the people of Ellendale. Over Sunday and Monday the smaller supply of soft water from the upper part of the Dakota was pumped into the system to furnish water for toilet and laundry uses, but later in the week the hard water from the deep well was pumped into the system and was used for sprinkling lawns and irrigating gardens.

The differences in the chemical composition of the upper and lower waters are shown by the following analyses:

Analyses of water from artesian wells at Ellendale, N. Dak.

[Samples collected June 28, 1921, by Howard E. Simpson; analyzed by H. B. Riffenburg. Parts per million.]

	Upper.	Lower.
Silica (SiO_2)	19	17
Iron (Fe)	2.0	2.3
Calcium (Ca)	30	204
Magnesium (Mg)	13	64
Sodium and potassium (Na+K)	990	320
Bicarbonate radicle (HCO_3)	495	171
Sulphate radicle (SO_4)	236	1,200
Chloride radicle (Cl)	1,150	70
Nitrate radicle (NO_3)	Trace.	Trace.
Total dissolved solids at 180° C	2,700	2,079
Hydrogen sulphide (H_2S)	----------	3.4
Total hardness as $CaCO_3$ (calculated)	128	772

The difference in head of the water from the two sources is as notable as the difference in chemical composition. In 1908, when the 1,385-foot well was drilled, the water is reported to have had a pressure at the surface of 193 pounds to the square inch, or sufficient to rise to a level 1,895 feet above sea level. This was a somewhat higher head than the original head reported for the 1,087-foot well and apparently about 300 feet higher than the head of the 1,087-foot well in 1908. So few wells have been drilled to the lower horizon that in 1923 the deep well at Ellendale still had a pressure of 50 to 60 pounds to the square inch, giving a head of about 115 to 140 feet above the surface, whereas the new 1,083-foot well at the time it was completed in December, 1923, had a pressure just sufficient to bring the water to the surface without overflowing. The deep well at La Moure, which also extends to the hard-water horizon, was tested in 1923 and was found to have a pressure of 97 pounds to the square inch.

Nearly all the artesian wells in the Edgeley quadrangle and adjacent region end in the so-called upper part of the Dakota sandstone and draw from the same general group of strata as the 1,087-foot and 1,083-foot wells at Ellendale. The present paper relates entirely to this upper part of the Dakota sandstone.

HISTORY OF ARTESIAN-WELL DRILLING IN THE EDGELEY QUADRANGLE.

The first well drilled to the Dakota sandstone in the Edgeley quadrangle was doubtless the well at Ellendale, which was put down in 1886. It was started with an 8-inch or 10-inch casing but was finished at the bottom with 3¾-inch casing, the lower 40 feet of which was perforated with ¾-inch holes. The next well drilled to the Dakota sandstone in the quadrangle of which there is any record is the city well at Edgeley, which is reported to have been 6 inches in diameter and to have been put down in 1892. C. E. Turnbaugh, who made the survey in 1923 for the present report, has been a driller in the Edgeley quadrangle since 1902. In so far as he has information these two wells were the only wells drilled to the Dakota sandstone prior to 1902. In 1902 he drilled a 2½-inch well for the village of Monango. About this time wells with small diameter came into use throughout the artesian basin, and owing to their low cost numerous 1¼ and 1½ inch wells were put down for farm supplies. Most of the artesian wells in the Edgeley quadrangle were drilled between 1904 and 1912; drilling was most active between 1905 and 1910, and very few artesian wells have been drilled since 1915.

ORIGINAL HEAD AND AREA OF ARTESIAN FLOW.

The original artesian head in different parts of the area can never be ascertained with great precision. The artesian-water map of South Dakota by Darton,[12] which was published in 1909 but which doubtless shows the approximate conditions at a considerably earlier time, indicates that in the southern part of the Edgeley quadrangle the area of artesian flow extended westward nearly to the 1,800-foot contour. It also indicates that in this part of the artesian basin the hydraulic gradient, or eastward decrease in artesian head, was about 4 feet to the mile. This agrees approximately with an original hydraulic gradient of 4⅓ feet to the mile from Highmore to Huron, S. Dak., as given by Powell[13] in 1890. According to Powell's report,[14] made in 1890, the pressure of the water in the well at Ellendale drilled in 1886 was 175 pounds to the square inch. According to Mr. J. R. Lacey, a resident of Ellendale, who was present when this well was drilled and who is probably the best-informed man on the entire history of the artesian wells at Ellendale, the pressure in this well was measured on the day the well was completed and was found to be 145 pounds. In the report by Nettleton,[15] published in 1892, a pressure of 115 pounds is given for this well, apparently based on measurements made by Nettleton in 1890. It seems reasonable to believe that the records of very high original pressure in the earliest wells drilled to the Dakota sandstone are approximately

[12] Darton, N. H., Geology and underground waters of South Dakota: U. S. Geol. Survey Water-Supply Paper 227, pl. 11, 1909.

[13] Powell, J. W., op. cit., p. 273.

[14] Idem, p. 269.

[15] Nettleton, E. S., op cit., pp. 67, 68, table opposite p. 74.

correct. Such pressures were doubtless maintained only a short time and hence were not corroborated by reliable measurements a few years later. It is evident also that those who made and reported the reliable measurements a few years later were not alert for data as to decline but rather assumed that the high pressures and flows were permanent. A pressure of 145 pounds at Ellendale would give a head of about 1,785 feet with reference to sea level—that is, it would be sufficient to raise the water in a casing or standpipe to an altitude of 1,785 feet above sea level. If the original head at Ellendale was 1,785 feet and the original hydraulic gradient 4 feet to the mile, the original west boundary of the area of artesian flow was about 16 miles west of Ellendale, at an altitude of about 1,850 feet above sea level.

An artesian-water map, by Darton and Willard,[16] of the Jamestown quadrangle, which lies immediately north of the Edgeley quadrangle, was published in 1909 but is based on studies made in earlier years. It shows the west margin of the area of artesian flow at the boundary between the Jamestown and Edgeley quadrangles to have been at about 1,725 feet above sea level. According to the available record, the city well at Edgeley, drilled in 1892, had an original pressure of 60 pounds to the square inch, or a head of about 1,690 feet with reference to sea level. Therefore if in 1892 the gradient was 4 feet to the mile, the west margin of the area of artesian flow lay about 6 miles west of Edgeley, or about 1,715 feet above sea level. The original pressure in the vicinity of Edgeley was probably somewhat greater than the pressure recorded in 1892.

In view of these data it seems reasonable to assume that the original west boundary of the area of artesian flow in the Edgeley quadrangle ranged from somewhat less than 1,800 feet above sea level in the northern part to somewhat more than 1,800 feet in the southern part and had an average altitude of fully 1,800 feet.

DECLINE IN HEAD FROM 1886 TO 1923.

The well at Monango, drilled in 1902, is reported to have had an original pressure of 70 pounds to the square inch, or a head of about 1,660 feet with reference to sea level—about 125 feet less than the Ellendale well in 1886, about 55 feet less than the Ellendale well in 1890, and about 30 feet less than the Edgeley well in 1892. Other data (given in the unpublished table) indicate a considerable drop in head prior to 1902.

During the period from 1902 to 1915, which was the period of active well drilling, the artesian head dropped rapidly. According to computations on 20 wells for which more or less satisfactory data

[16] Willard, D. E., U. S. Geol. Survey Geol. Atlas, Jamestown-Tower folio (No. 168), 1909.

are available, the average annual decline during this period was 12.7 feet, which for the whole period would amount to 165 feet.

During the period from 1915 to 1920 the decline, according to similar computations on 12 wells, averaged about 4 feet a year, or about 20 feet for the period. During the period from 1920 to 1923 the decline, according to computations on 20 wells, averaged about 4 feet a year, or about 12 feet for the period.

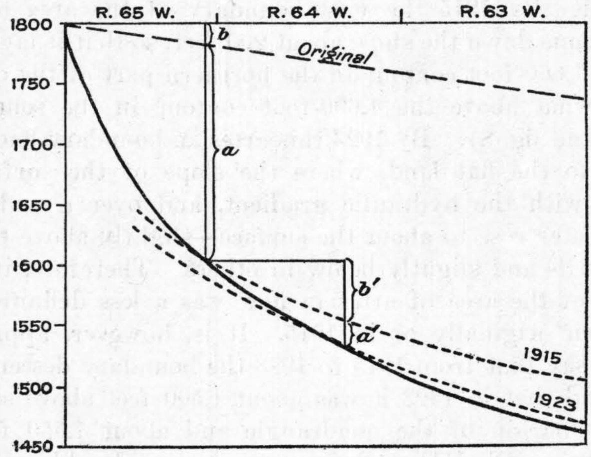


FIGURE 8.—Generalized east-west section of the area of artesian flow in the Edgeley quadrangle, N. Dak., showing approximately the profile of the land surface, the original hydraulic profile, and the hydraulic profiles in 1915 and 1923. The hydraulic profile for any particular year indicates how high the water from the upper part of the Dakota sandstone would rise at each point along the section in that year. *a*, Decline in head prior to 1915 in wells at position of artesian boundary in 1915; *b*, original difference in head between wells at original boundary and wells at boundary in 1915; *a′*, decline in head from 1915 to 1923 in wells at position of artesian boundary in 1923; *b′*, difference in head in 1915 between wells at boundary in 1915 and wells at boundary in 1923. $a+b$, Descent of artesian boundary prior to 1915; $a'+b'$, descent of artesian boundary from 1915 to 1923; $(a+b)+(a'+b')$, total descent of artesian boundary prior to 1923.

The foregoing computations are based on available wells within the original area of artesian flow in the Edgeley quadrangle and in a belt several miles wide adjacent to this quadrange on the south. They indicate a decline of about 200 feet from 1902 to 1923 and a considerably greater decline from 1886 to 1923. Computations that take into account the geographic distribution of the wells (see pp. 84 and fig. 8) indicate, however, that the average decline for the entire area has not been quite so great. On the assumption that the original pressure in the Ellendale well was 145 pounds to the square inch, they indicate that the decline in the southeast corner of the quadrangle amounted to over 300 feet, but that the average for the entire area was more nearly 250 feet. If the original pressure at Ellendale was 175 pounds to the square inch the total decline was about 70 feet greater.

SHRINKAGE IN THE AREA OF ARTESIAN FLOW.

According to the lower assumption as to the original head, the area of artesian flow originally extended westward to an altitude of somewhat less than 1,800 feet near the north margin of the Edgeley quadrangle and to an altitude of somewhat more than 1,800 feet near the south margin. In 1902 it apparently still extended to an altitude of 1,700 feet or more, except possibly near the north margin of the quadrangle. By 1915 the west boundary of the area of artesian flow had come down the slope about 200 feet, so that it lay somewhat below the 1,600-foot contour in the northern part of the quadrangle and somewhat above the 1,600-foot contour in the southern part (Pl. VII and fig. 8). By 1923 this artesian boundary had migrated eastward to the flat land, where the slope of the surface nearly coincided with the hydraulic gradient, and over a wide belt the artesian water rose to about the surface—slightly above the surface in some wells and slightly below in others. Therefore, in 1923 the boundary of the area of artesian flow was a less definite line than it had been originally or in 1915. It is, however, approximately correct to say that from 1915 to 1923 the boundary descended about 75 feet, and that in 1923 it was about 1,500 feet above sea level at the north margin of the quadrangle and about 1,550 feet at the south margin (Pl. VII and fig. 8). A considerable part of this descent occurred between 1920 and 1923. According to the lower assumption as to the original head, the total descent of the west boundary of the area of artesian flow from the time the first wells were drilled until 1923 was about 275 feet. The belt in which flowing wells were originally obtained but in which the wells have ceased to flow is about 10 miles wide in the northern part of the quadrangle and 5 miles wide in the southern part (Pl. VII). Fully half of this belt has "gone dry" in the 8-year period since 1915, during which only a few wells were drilled.

INCREASE IN HYDRAULIC GRADIENT.

A geographic analysis of the data indicates that the decline in artesian head has been greater along the east margin of the Edgeley quadrangle than farther west and hence that the hydraulic gradient has increased. According to the best information available, the original gradient was only about 4 feet to the mile, whereas the gradient in 1923 was about 10 feet to the mile in the eastern part of the quadrangle and fully 15 feet to the mile west of the 1,600-foot contour (fig. 8). These figures may be considerably in error, the original gradient especially being in doubt, but the available records of decline from year to year in artesian head and in depths to the water level in wells that have ceased to flow give evidence of relatively small decline in head in the western part of the original area of artesian flow. They seem to lead to the significant conclusion that the effect of the great decline in head becomes slight or dies out entirely long before the western outcrops of the sandstone are reached.

CORRELATION OF DECLINE IN HEAD WITH DESCENT OF ARTESIAN BOUNDARY.

According to the computations, the results of which have been given, the descent of the artesian boundary was less than the average decline in head during the period prior to 1915 but much greater than the average decline during the period from 1915 to 1923. To the casual reader these differences may appear to be discrepancies in the results. On account of the fragmentary and uncertain data in regard to conditions in the early years of artesian development, no claim of accuracy can be made for these computations, but it should be noted that the results are about as would be expected when the topography and the changes in hydraulic gradient are taken into consideration.

In Figure 8 the vertical distance a represents the decline in head prior to 1915 at the point shown, and the vertical distance $a+b$ represents the descent of the artesian boundary prior to 1915. Because of the steep slope of the land surface the large decline in head did not produce any great lateral movement of the artesian boundary. For this reason and because of the slight original hydraulic gradient the descent of the artesian boundary ($a+b$) was only slightly greater than the decline in head (a) at the point shown. But farther east the decline in head was greater than at this point, as is indicated in Figure 8 by the increased vertical distance to the east between the original hydraulic profile and the hydraulic profile in 1915. Hence the vertical distance through which the artesian boundary descended during this early period was somewhat less than the average decline in head.

The vertical distance a' represents the decline in head from 1915 to 1923 at the point shown, and the vertical distance $a'+b'$ represents the descent of the artesian boundary during this period. Because of the more gentle slope of the land surface in the belt through which the artesian boundary had to pass in this later period the relatively small decline in head (a') produced fully as great a lateral movement of the artesian boundary as had been produced by the great decline (a) in the period prior to 1915. For this reason and because of the greater hydraulic gradient the descent of the artesian boundary ($a'+b'$) was much greater than the decline in head at the point shown (a') and also much greater than the average decline in head.

YIELD OF FLOWING WELLS AND DECLINE IN YIELD.

The flow of the 3¾-inch well at Ellendale drilled in 1886 was 600 gallons a minute according to Powell's report,[17] published in 1891, and 700 gallons a minute in 1890 according to the Nettleton report,[18] published in 1892. The original flow of the 6-inch well at Edgeley drilled in 1892 is reported to have been 500 gallons a minute.[19] The 2½-inch well drilled at Monango in 1902 is reported by C. E. Turnbaugh, the driller, to have had an original flow of only 45 gallons a minute.

According to an estimate by Hard, the original discharge of 1¼-inch wells drilled prior to 1915 in the Edgeley and La Moure quadrangles was about 50 to 100 gallons a minute. According to the estimates of Turnbaugh and other drillers and well owners, as given in the unpublished table, the original discharge of 116 wells drilled in the Edgeley quadrangle from 1902 to 1914, inclusive (not including the deep well drilled at Ellendale in 1908 to a deeper horizon), was only 22⅓ gallons a minute. These 116 wells were nearly all 1¼ or 1½ inches in diameter.

Hard also estimated for the Edgeley and La Moure quadrangles that in 1915 the flow from 1¼-inch wells was 5 to 10 gallons a minute near the west side of the area of artesian flow and 15 to 40 gallons farther east. However, the average discharge of 20 wells measured in 1915 by H. M. Derr,[20] State engineer of South Dakota, in Brown County, which lies south of these quadrangles, was only about 11 gallons a minute.

The flow of 41 wells measured by Hard in the Edgeley quadrangle in 1919 and 1920 ranged from a fraction of 1 gallon a minute to 20 gallons a minute and averaged 7⅔ gallons.

In 1923 the flow of 111 artesian wells was measured by Turnbaugh—all in the Edgeley quadrangle except a few that were just outside. This list included nearly but not quite all the flowing wells in the quadrangle. The 111 wells were found to have an aggregate flow of 343 gallons a minute, or an average flow of 3.09 gallons a minute. With few exceptions the flows were measured after the wells had been opened as much as possible, and the results therefore represent more than the actual discharge of the wells in their normal condition.

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[17] Powell, J. W., op. cit., p. 269.

[18] Nettleton, E. S., op. cit., table opposite p. 74.

[19] Darton, N. H., U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, p. 661, 1896.

[20] Derr, H. M., op. cit., pp. 177–187, 244–248.

SPECIFIC CAPACITIES OF FLOWING WELLS.

The specific capacity of a flowing well is its flow per foot of head. If there is no change in the intake facilities of a well, its specific capacity will remain nearly the same whether the head is high or low. Thus if the specific capacities of the wells that tap the Dakota sandstone can be determined they will give a check on the reported flows of the wells in the earlier years when the heads were high and will also give a clue as to the permeability of the sandstone and hence as to the rate of recharge.

For 23 wells in the Edgeley quadrange there is fairly reliable information as to head and flow, which was used in calculating the specific capacities of these wells. For four of these wells check calculations could be made, because this information was available for different years and hence for different heads. In one of these four wells the specific capacity was 0.40 gallon a minute for each foot of head in 1906 and 0.25 in 1920; in another it was 0.15 in 1909 and 0.24 in 1915; in a third it was 0.28 in 1902 and 0.29 in 1920; and in the fourth it was 0.09 in 1920 and 0.09 in 1923. Thus the calculations for different years and very different heads agreed as closely as could be expected.

The data in regard to the specific capacities of the 23 wells for which calculations could be made are summarized in the following table:

Specific capacities of wells in the Edgeley quadrangle.

Diameter (inches).	Number of wells.	Specific capacity (gallons a minute for each foot of head).		
		Maximum.	Minimum.	Average.
6	1	3.62	3.62	3.62
3¾	1	2.64	2.64	2.64
2½	1	.29	.29	.29
2	4	1.40	.57	.80
1½	3	.57	.20	.35
1¼	12	.36	.09	.22
1	1	.14	.14	.14
1 to 2 (inclusive).	20	1.40	.09	.25

If the average flow of the small wells is one-fourth gallon a minute for each foot of head, then the average flow should have been 50 gallons a minute when the head was 200 feet, 25 gallons when it was 100 feet, 10 gallons when it was 40 feet, 3 gallons when it was 12 feet, and so on.

TOTAL DISCHARGE OF FLOWING WELLS.

As the water in the Dakota sandstone comes from the west and moves in general toward the east, a study of discharge, recharge, and depletion of the artesian-water supply should obviously relate to an east-west belt extending across the entire area of artesian flow unless a complete survey of the entire basin can be made. Hence for this purpose calculations have been made for the tract covered by T. 129 N., Rs. 48–65 W., and not for the Edgeley quadrangle (fig. 7, p. 76).

It was estimated by Darton[21] that in 1896 the total discharge from flowing wells which ended in the Dakota sandstone in the area that he covered was 104,000 gallons a minute. This area included most of the area of artesian flow of the Dakota sandstone in North and South Dakota and had a north-south extent of nearly 300 miles. His estimate therefore gives an average discharge of a little more than 2,000 gallons a minute for an east-west row of townships in the area. As most of the strong wells were in South Dakota, the average for the part of the area that lies in North Dakota must have been much less than 2,000 gallons a minute. The only well in the T. 129 row shown by Darton's report was the Ellendale well, with a flow of 700 gallons a minute.

In 1923, in connection with the enforcement of the artesian-water law, practically all flowing wells in this row of townships were inspected by Howard E. Simpson, water geologist of the North Dakota Geological Survey, and his deputy, C. E. Turnbaugh. The data obtained in this inspection were generously furnished by Professor Simpson for use in this report. They show that in T. 129 N., Rs. 50 to 65 W., inclusive, there were 320 flowing wells supplied by the Dakota sandstone, which were normally discharging an aggregate of 965 gallons a minute, or an average per well of 3.02 gallons a minute. In addition were the wells that supplied the waterworks in six towns and five farm wells that were closed except when the faucets were turned on. It was estimated that an average of about 40 gallons a minute was drawn from these wells, making an aggregate flow of 1,005 gallons a minute. It was estimated by Simpson and Turnbaugh that the aggregate flow in this row of townships in 1923 was about one-half the aggregate flow in 1920—that is, that the flow from all wells in this row of townships in 1920 was about 2,000 gallons a minute, or about 6 gallons a minute per well. No flowing wells were reported in T. 129 N., Rs. 48 and 49 W.

On the basis of all available data and with the assumption that the history of well drilling in the T. 129 row was similar to that given for the Edgeley quadrangle, a rather elaborate calculation was made of the quantity of water that has been discharged from the Dakota sandstone through wells in this row of townships. This calculation gave an average discharge during the 38-year period from

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[21] Darton, N. H., U. S. Geol. Survey Seventeenth Ann. Rept., pt. 2, p. 609, pl. 69, 1896.

1886 to 1923 of somewhat less than 3,000 gallons a minute. The peak discharge doubtless occurred at some time between 1905 and 1910 and probably did not exceed 10,000 gallons a minute. It is recognized that these estimates may be very inaccurate, but they are probably as good as can ever be made and are believed to be worth presenting in order to give some tangible conception of the quantities of water that are involved and the stage of depletion that has been reached. It is believed that the total quantity of artesian water discharged at the surface in an average row of townships in this artesian basin in North Dakota did not exceed the quantity represented by these figures—that is, 3,000 gallons a minute for a period of 38 years. No estimate can be made of the underground waste through leaky casings. However, it is generally believed by those best qualified to judge that the aggregate underground waste is not very large, because of the great thickness of plastic clay that tends to seal the old wells when the casing becomes corroded.

BENEFICIAL FLOW AS ESTIMATED BY THE STATE GEOLOGICAL SURVEY.

On the basis of the information obtained in the inspection a careful estimate was made by Professor Simpson of the extent to which each of the 320 wells can be reduced in order to stop all unnecessary discharge without depriving the farmer of any beneficial use or working any hardship. The term "unnecessary discharge" is used to designate the discharge that serves no useful purpose. Reasonable allowances were made for a flow of water that will run to waste but will be necessary to prevent freezing of the pipes or clogging of the well. The results of this work showed that by stopping the unnecessary discharge the flow can be reduced to 377 gallons a minute from the 320 wells, or to an average of 1.18 gallons a minute per well. This makes the aggregate beneficial flow amount to 417 gallons a minute from existing wells in this row of townships, including the necessary flow from the waterworks wells and the closed farm wells.

RATE OF RECHARGE.

An effort was made to estimate for the T. 129 row of townships the rate at which the water in the Dakota sandstone is percolating eastward in the direction of the hydraulic gradient. It was assumed that, whereas the townships both to the north and to the south have similar artesian-water developments, this row of townships is supplied by the artesian water directly west of it and neither draws from nor contributes to the adjacent townships. Such an estimate would be of great practical value, because it would serve as a basis for judging how much further the discharge must be reduced, either by natural lowering of the head or by voluntary or enforced conservation, before a balance is struck between discharge and recharge. Unfortunately the information in regard to both thickness and texture of the water-bearing sandstone strata is so meager and unsatisfactory that it is impossible to make any estimate in which much confidence can be placed. Calculations based on Slichter's formula [22] show, however, that if the hydraulic gradient is 10 feet to the mile and the sandstone strata which supply the wells under consideration have a thickness of 60 feet, a porosity of 35 per cent, and an effective size of grain of 0.17 millimeter—the same as that of the St. Peter sandstone as determined in numerous tests [23]—the rate of recharge or eastward percolation is about equal to the 417 gallons a minute estimated by Simpson as the quantity needed for present beneficial use without any unnecessary discharge and without allowing anything for possible underground leakage. There are no good reasons for believing that the rate of recharge is greater than this amount.

It is at least interesting to recall that in 1890, when the artesian wells still had tremendous pressure and flow, Major Powell, at that time Director of the United States Geological Survey, estimated in a hearing before a Congressional committee, on an entirely different basis, that the total recharge amounted to about 475 gallons a minute for each row of townships and the recoverable recharge to one-half that amount.[24]

WITHDRAWAL OF STORED WATER AND COMPRESSION OF THE DAKOTA SANDSTONE.

The foregoing considerations raise the question as to the source of the artesian water that has been discharged during the last 38 years and that is being discharged at present. If the rate of discharge in the area of artesian flow has been more rapid than the rate at which water percolated into the sandstone underlying this area, some of the water discharged must have been derived from storage in the sandstone underlying the area. This requires a reduction in the interstitial space occupied by water. Either the water was replaced in some of the interstices by gas, or else the sandstone has a volume elasticity, so that, as the buoying force of artesian pressure within the sandstone was relieved, the sandstone underwent a certain amount of

[22] Slichter, C. S., Field measurements of the rate of movement of underground water: U. S. Geol. Survey Water-Supply Paper 140, pl. 2, 1905.

[23] Dake, C. L., The problem of the St. Peter sandstone: Missouri Univ. School of Mines and Metallurgy Bull., August, 1921, pp. 152–177. See also Meinzer, O. E., U. S. Geol. Survey Water-Supply Paper 489, pp. 119, 120, 1924.

[24] Powell, J. W., op. cit., p. 274.

compression in which its total interstitial space was reduced by a volume equal to the volume of the stored water that was discharged. The theory of gas accumulation is believed to be untenable. In his unpublished report Hard states that the gas discharged by some of the wells seems to occur as an unsaturated solution in the artesian waters of the Dakota sandstone and apparently is released from solution by the reduction of pressure incident to the rise of the water to the surface. There is no indication that gas occurs in the sandstone in the gaseous state at the present time.

If the theory of gas accumulation is dismissed the theory of volume elasticity and resulting compression of the sandstone is supported by two other lines of evidence—the apparently rapid dying out toward the west of the decline in artesian head, and the long period required for a flowing well to recover its full pressure after it has been closed and a pressure gage has been attached.

If the formation were perfectly rigid any lowering in artesian head ought to result in a prompt readjustment of the hydraulic gradient all the way to the outcrop from which the water is derived, hundreds of miles away, and ought to produce a somewhat more rapid percolation in all this distance. The comparatively small decline in the water level in wells near the west side of the original area of artesian flow, however, seems to indicate that in all these years readjustment of the hydraulic gradient has not extended west many miles, or, at least, that long before the western outcrops are reached the readjustment becomes very small. If this is true the hydraulic profile is like the profile of a water table where there has been depletion of storage in the vicinity of heavily pumped wells; it is not the profile that would be developed in a rigid pressure system.

In testing the artesian pressure of the flowing wells Hard found that after a well was closed and the gage was attached the pressure would increase gradually for some time. This confirmed the observations of earlier investgators.[25] Different wells behaved very differently, but the time required for the pressure to reach a maximum in some wells amounted to several hours. When the Ellendale well was tested in 1890 it was found that a few hours was required for the water to reach its maximum pressure after the flow had been shut off.[26] The explanation seems to be that the water-bearing bed has a certain amount of volume elasticity, that it became compressed when the artesian pressure was relieved, and that before the pressure in the well could again reach the pressure that was general in the formation sufficient time had to elapse to allow the water to

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[25] Nettleton, E. S., op. cit., pp. 40–74.
[26] Idem, p. 68.

percolate into the depleted and compressed part of the formation immediately surrounding the well and to expand the interstitial space.

If the foregoing calculations were accurate they would afford a basis for computing the amount of compression which, according to this theory, was involved. If in the last 38 years the average rate of discharge was 3,000 gallons a minute and the average rate of recharge only 500 gallons a minute, the average withdrawal from storage amounted to 2,500 gallons a minute. If the area of depletion consists of the 18 townships described as T. 129 N., Rs. 48-65 W., a total discharge of 3,000 gallons a minute for 38 years would amount to a layer of water 5.3 inches deep over all of this area, and a withdrawal from storage of 2,500 gallons a minute would amount to a layer of water 4.4 inches deep.

The first well at Ellendale, according to the log on page 78, reached the Dakota sandstone at a depth of 1,035 feet and penetrated the Dakota 52 feet. The beds above the Dakota are chiefly soft shale, which, with the water they contain, must have a specific gravity of about 2. Hence these beds, owing to their weight, exert a pressure equal to that of a column of water about 2,070 feet high, or 898 pounds to the square inch. If the original head of the artesian water in this well was 333 feet at the surface (145 pounds to the square inch), then the artesian pressure at the top of the Dakota sandstone was that of a column of water 1,368 feet high, or 594 pounds to the square inch. Therefore, 594 pounds to the square inch of the pressure exerted by the beds that overlie the Dakota sandstone was supported by the water in the sandstone, and only 304 pounds by the sandstone itself. If at any point within the area of artesian flow the head at the surface was as great as the depth to the Dakota sandstone the artesian pressure must have been great enough virtually to float the overlying beds. As the head at Ellendale has declined approximately 333 feet (145 pounds to the square inch) the burden placed on the sandstone has increased from about 304 pounds to 449 pounds, or 47½ per cent. If the original pressure in the Ellendale well was 175 pounds the burden has increased 61⅓ per cent. It has long been known that at least slight compression of water-bearing beds may result from additional loads at the surface, such as tides or even railroad trains.[27] It is also well known that, other things being equal, the porosity of rocks decreases with depth because of increase in the weight they must support.[28] It seems within the range of

[27] Veatch, A. C., Fluctuations of the water level in wells, with special reference to Long Island: U. S. Geol. Survey Water-Supply Paper 155, pp. 65, 75, 1906.

[28] Sorby, H. C., On the application of quantitative methods to the study of the structure and history of rocks: Geol. Soc. London Quart. Jour., vol. 64, p. 214, 1908. Meinzer, O. E., U. S. Geol. Survey Water-Supply Paper 489, p. 8, 1924.

possibility, therefore, that the upper part of the Dakota sandstone, which is here being considered, should have undergone a compression of a few inches—probably less than 1 per cent—as a result of the release of the expansive force of artesian pressure and a consequent increase of about one-half in the load upon the formation.

In order to obtain a more adequate basis for conclusions as to the behavior of the artesian water precise data are greatly needed (1) as to the mechanical composition, porosity, and permeability of the sandstone in each stratum of the Dakota sandstone and (2) as to the fluctuation of the artesian head in flowing wells and of the water level in nonflowing wells that end in the Dakota sandstone—in the areas of artesian flow, at the outcrops, and so far as possible at intermediate points. These observations on artesian head and water levels are needed not only to determine the hydraulic profile and its progressive modification but also to ascertain to what extent seasonal fluctuations in the water table at the outcrops are transmitted to the remote parts of the formation.

BENEFICIAL EFFECT OF THE CONSERVATION POLICY ADOPTED BY THE STATE OF NORTH DAKOTA.

All the theoretical considerations above set forth have an intensely practical bearing on the policy of conservation of the artesian water that has been adopted by the State of North Dakota. The great and progressive decline in artesian head is well established, and the desirability of preventing further decline and of saving the wells that are still flowing is generally recognized. The only question that remains is whether the decline can be stopped by the measures that are being put into effect. Although satisfactory data as to the rate of recharge are lacking, enough information has been obtained on the subject to indicate that the conservation already effected and the further conservation outlined by Howard E. Simpson, the water geologist of the State Geological Survey, will tend to keep the wells flowing.

Decline in artesian head will cease when a balance is reached between the discharge from the artesian wells and the natural recharge. Apparently this balance has not yet been reached. Between 1920 and 1923 there was considerable decline, and a number of wells ceased flowing. The annual recharge for each row of townships across the area of artesian flow east of the Coteau du Missouri is probably less than the 1,000 gallons a minute that was being withdrawn in the T. 129 row in 1923. The decrease in flow from 2,000 to 1,000 gallons a minute from 1920 to 1923 has been due only in part to natural decline. In large part it is due, according to the observations of Simpson and Turnbaugh, to the reduction of discharge openings in the artesian wells which have been made by the well owners since the artesian-water law went into effect, March 10, 1921. The reductions were made in part as a result of education and the influence of the drillers through the North Dakota Well Drillers Association. It was also estimated by Simpson that in T. 129 N., Rs. 63, 64, and 65 W., largely owing to the detailed work done in these townships by Hard, the reduction from 1920 to 1923 amounted to fully two-thirds. It is probably no exaggeration to say that the saving that has been accomplished in this row of townships through the reduction of the discharge openings of wells since the law was enacted is as great as the waste that was still going on in 1923—in other words, that one-half of the possible conservation had already been accomplished in 1923, largely through the intelligent, reasonable, and helpful campaign of education conducted by the State Geological Survey. Obviously so great a saving must have an appreciable effect in checking the rate of decline and in keeping wells flowing that would otherwise have failed by this time or would fail in the near future.

Although the rate of recharge is not definitely known, it probably amounts to a few hundred gallons a minute for each row of townships but not to as much as 1,000 gallons a minute. For the sake of seeing more clearly what will be the beneficial effect of carrying out the recommendations for further reductions made by the State water geologist, let it be assumed that the rate of recharge is equal to the 417 gallons a minute of flow recommended by him. In 1923 this amount of water was being discharged by the 48 strongest wells among the total number of a little more than 330 wells that were inspected. Obviously with this amount of recharge and no further attempt at conservation, most of the available supply will ultimately be discharged by a few of the strongest wells, and a large majority of the wells that are now flowing will either fail entirely or will not yield enough for practical purposes. On the other hand, with this amount of recharge, if all reductions are made as recommended, there will be no further decline and all the existing flowing wells will be saved. The basal assumption may be inaccurate, but the principle illustrated by it is sound. It is possible that the recharge is so small or that the underground leakage is so considerable that the ultimate failure of most of the flowing wells can not be prevented even if the program of the State Geological Survey is faithfully carried out, but the conditions are certainly hopeful enough to justify a thorough trial of this program. Every owner of a flowing well in this artesian basin should, for his own good and that of his neighbors, give his utmost support to this program for saving the artesian water.

The question is often asked whether conservation in North Dakota can be effective without conservation in South Dakota. It is highly desirable that the States should cooperate in this movement. However, the present investigation has shown that the effects of depletion in one area are not rapidly transmitted to other areas. Doubtless wells near the State line in North Dakota will suffer by waste from near-by wells in South Dakota, but this should not deter the State of North Dakota from proceeding with its well-planned program of conservation. Such a program is of course equally desirable in South Dakota.