GROUND WATER IN THE ORDOVICIAN ROCKS NEAR WOODSTOCK, VIRGINIA

By George M. Hall

INTRODUCTION

Woodstock, the county seat of Shenandoah County, Va., is one of the many prosperous towns in the Valley of Virginia. It is situated on the Southern Railway about 30 miles south-southwest of Winchester, at an altitude of 820 feet above sea level. The population of the town is 1,580, according to the United States Census of 1920. The position of the town is shown in Plate 7. The main highway in the valley passes through Woodstock, and the tourist traffic is heavy. Many automobilists use this route to and from the South and in local tours to the scenic attractions of the area. Numerous picturesque caverns occur in the limestone of the area and are visited by thousands annually. The Valley of Virginia was a battle ground throughout the Civil War and contains many famous spots where the conflicting forces clashed.

The surrounding region is a rich agricultural country devoted largely to orchards and dairy farms, and it annually produces large and valuable crops. Most of the business for a radius of a dozen miles or more is transacted in Woodstock, making the town prosperous. The town is essentially a residential and merchandising community and not an industrial center. The creamery of the Chapin-Sack Corporation [1] and a flour mill are the only important industrial plants in Woodstock.

The United States Geological Survey has received numerous inquiries concerning the occurrence of water in the Cambrian and Ordovician limestones of the Valley of Virginia. Small supplies sufficient for an ordinary farm are usually available at relatively shallow depths, and a few wells yield large quantities, but in many places supplies adequate for industrial or municipal purposes are difficult to obtain. The question is frequently asked whether deep wells will yield large supplies. Recently the Chapin-Sacks Corporation drilled a well at Woodstock to a depth of 1,550 feet and encountered no water below the 250-foot level. The information obtained from this

[1] Now operated by Southern Dairies (Inc.).

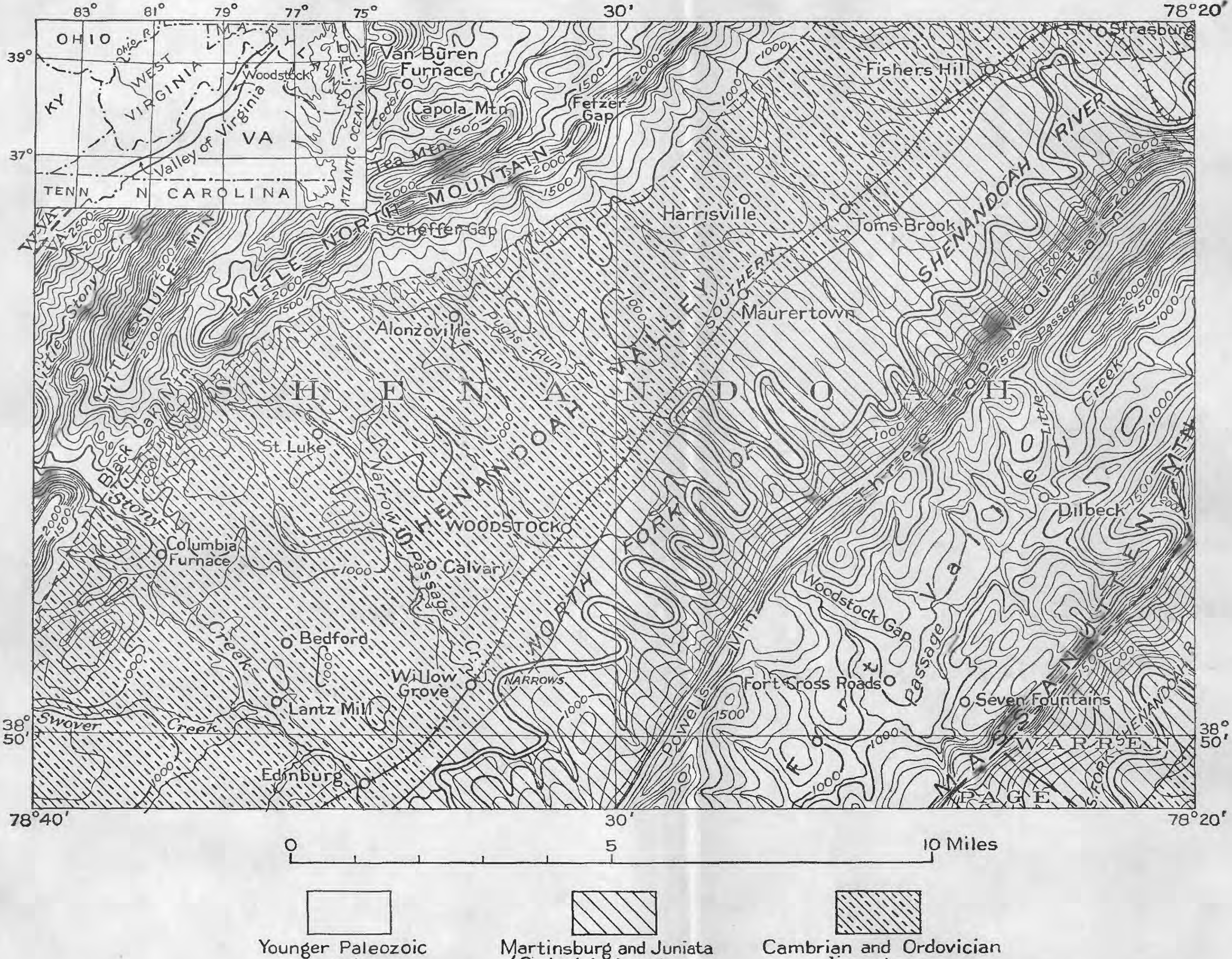
deep well, together with other data collected during two brief visits—one in July and the other in October, 1924—form the basis for this brief contribution. This deep well afforded a valuable opportunity to study the possibility of obtaining water supplies from considerable depths. The results of this study are applicable not only to the immediate vicinity of Woodstock but in some degree to other parts of the Valley of Virginia. Only a few analyses of water from the Ordovician rocks in these valleys have heretofore been published, and therefore six samples were taken and analyzed in the laboratory of the Geological Survey. (See pp. 63–65.)

The writer acknowledges the kindness of Mr. J. B. Eckhardt, formerly manager of the Chapin-Sacks Corporation, and of Mr. Harvey Kessler, manager of the Woodstock Creamery, and is appreciative of the valuable information supplied by Mr. William J. Gochenour, driller of the deep well.

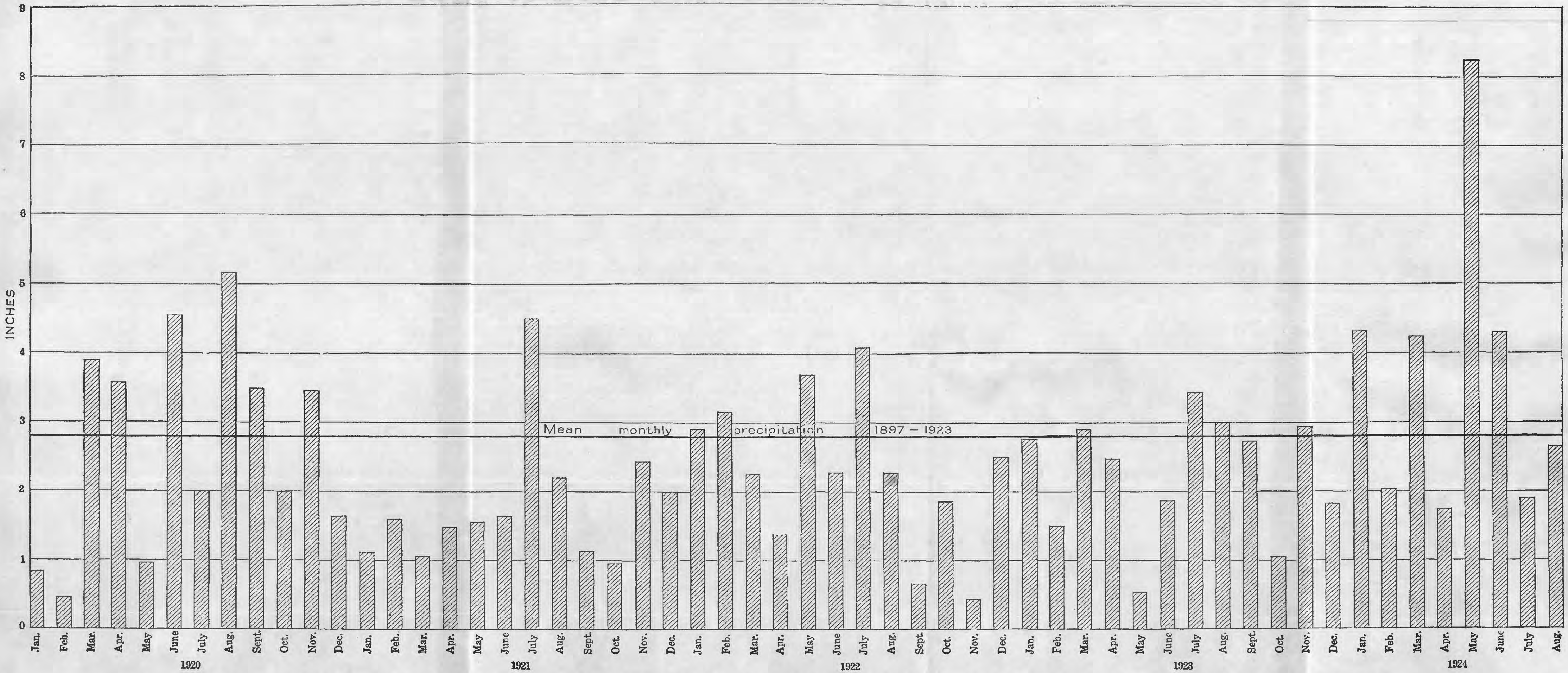
CLIMATE AND ITS EFFECT ON THE WATER TABLE

The climate of Woodstock is relatively mild, and usually 180 days or more intervenes between the last killing frost in spring and the first in autumn. The mean annual temperature is 53.4° F.; temperatures of more than 100° or less than 0° are uncommon. The mean annual precipitation during a period of 27 years, from 1897 to 1923, was 33.55 inches. There is considerable variation from year to year in the amount of precipitation, as is shown in Figure 8. The maximum during the period was 44.37 inches, in 1901, and the minimum was 25.19 inches, in 1914. During the 10 years ending 1923 the average annual precipitation was lower than that of the preceding decade. As shown in Figure 9, the summer months May to August have an excess over the remainder of the year, and each month of that period averages more than any one of the remaining eight months. The three years 1921 to 1923 were relatively dry, with an average precipitation of only 27.44 inches, or 6.11 inches below the annual mean. As shown in Plate 8, during this period only 9 of the 36 months had an excess of precipitation over the monthly average for the period from 1897 to 1923, and 16 months had a total precipitation of less than 2 inches. This unprecedented period of drought resulted in a small discharge of the streams and in a low level of the water table.

The deficiency in precipitation in these three years amounted to more than 18 per cent of the annual mean, and many of the wells and springs failed. During this period the 185-foot drilled well in the Gravely orchard, west of Woodstock, in which the water usually stands within 40 feet of the top, went dry, apparently indicating a drop of as much as 140 feet in the water table. The water



GENERALIZED GEOLOGIC MAP OF THE VICINITY OF WOODSTOCK, VA.



MONTHLY PRECIPITATION AT WOODSTOCK, VA., FROM JANUARY, 1920, TO AUGUST, 1924, COMPARED WITH THE MEAN MONTHLY PRECIPITATION FOR THE PERIOD 1897 TO 1923

FIGURE 8.—Annual precipitation at Woodstock, Va., 1897–1923

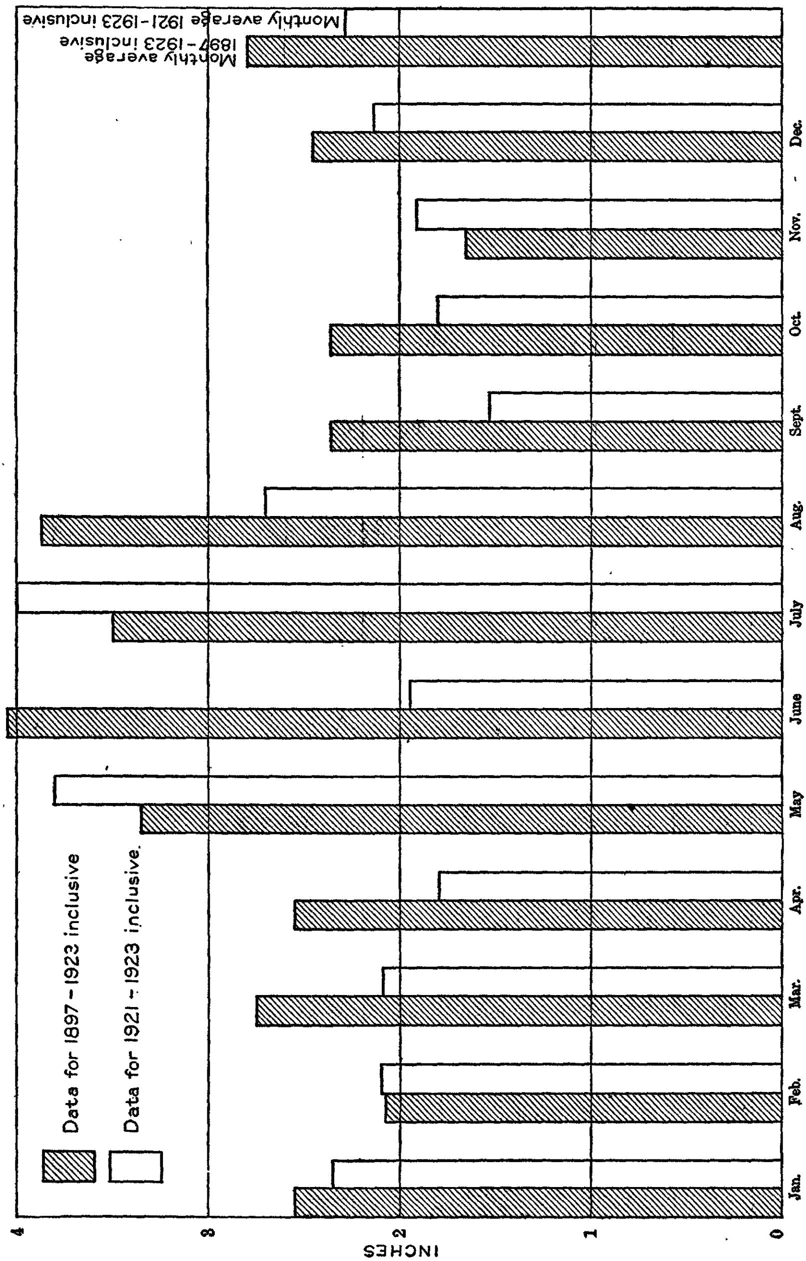


FIGURE 9.—Monthly distribution of precipitation at Woodstock, Va., 1897–1923 and 1921–1923

in the dug well on Spring Street, which now overflows and is reported to have overflowed for a number of years prior to the dry summer of 1923, dropped to a level 40 feet below the surface. This very considerable drop in the level of the water table caused the failure of many wells that had been considered permanent, and a serious water shortage resulted in both town and country.

The first six months of 1924 were decidedly wetter than the three preceding years, and a precipitation of 26.01 inches was recorded for that period, compared with 27.44 inches for all of 1923. At the beginning of the winter of 1923–24 the level of the water in the wells rose. By the end of July, 1924, the water table was not only back at its normal level but was slightly higher than normal. Numerous small hillside springs that had been dry began to flow. According to local observers these springs flow only in wet years. The Gravely orchard well and the dug well in Spring Street completely recovered.

On the writer's second visit to the region, October 10–12, 1924, although the rainfall in July and August had been only 1.90 and 2.65 inches, respectively, the Spring Street well was still overflowing at apparently the same rate as in July, and there was no reported shortage of water, although the temporary springs mentioned above had ceased to flow. Apparently the heavy rains of the first half of 1924 had raised the water table and had completely replenished the ground-water supply, so that the deficient rainfall of July and August had no serious effect.

STREAMS

The region is drained by the North Fork of Shenandoah River. With the exception of this river and a few tributaries that rise in the mountains to the west and flow across the valley the region is almost without streams. In a few places, however, large springs form branches that join the larger streams. Most of the run-off drains into sink holes, which are very numerous, and thus a large part of the precipitation becomes ground water. Most of the sink holes are dry throughout the year or hold water for only a few hours after a storm, but some always contain water, and these form the only ponds in the region.

The North Fork of the Shenandoah flows northeastward through the valley in a series of deeply intrenched meanders to meet the South Fork at the north end of Massanutten Mountain. It is a fast-flowing stream that is used to generate electric power. The river flows within a mile of Woodstock but is not visible from the town. To appreciate the full beauty of this stream one must see it from Massanutten Mountain.

A gaging station was maintained from 1899 to 1906 by the United States Geological Survey on the North Fork of the Shenandoah at a point near Riverton, about 25 miles below Woodstock. The maximum discharge recorded[1] at this station is 21,630 cubic feet a second, in April, 1901, and the minimum 90 cubic feet a second, in August, 1900, and October, 1904. Passage Creek and several other tributaries enter the river between Woodstock and Riverton.

Analyses[2] were made of a series of samples of water taken from the Shenandoah at Millville, W. Va., in 10-day periods extending from September 12, 1906, to September 9, 1907. The average of these analyses is given below:

Analysis of Shenandoah River water

[Mean of series of samples September 12, 1906, to September 9, 1907. Parts per million]

Turbidity	31
Suspended matter	39
Coefficient of fineness	1.64
Total iron	.9
Silica	15
Iron	.08
Calcium	32
Magnesium	8.2
Sodium and potassium	6.7
Carbonate radicle	1.3
Bicarbonate radicle	132
Sulphate radicle	6.2
Nitrate radicle	2.6
Chloride radicle	3
Total dissolved solids	140

Although Millville is more than 50 miles downstream from Woodstock and is below the junction of the North and South Forks, the figures are doubtless representative of the North Fork, because both forks of the river flow almost continuously over rocks like those surrounding Woodstock.

SURFACE FEATURES

The Woodstock area is in the Appalachian Valley province. The large expanse of valley which lies between the Blue Ridge and the Appalachian Valley Ridges and which is commonly called the Valley of Virginia extends in a general northeasterly direction from the southern to the northern boundary of the State, a distance of more than 300 miles, and ranges in width from 1½ to 20 miles. At Potomac River the floor of the valley is less than 500 feet above sea

[1] Stevens, G. C., Surface water supply of Virginia: Virginia Geol. Survey Bull. 10, 1916.
[2] Dole, R. B., Quality of surface waters in the United States, Part I: U. S. Geol. Survey Water-Supply Paper 236, 1909.

level, but in the southern part of the State it is much higher and reaches in places 2,500 feet. From Harrisonburg to Strasburg, a distance of 45 miles, the valley is divided lengthwise into two parts by Massanutten Mountain. The town of Woodstock is situated in the part that lies northwest of this mountain and is drained by the North Fork of Shenandoah River. This part of the Valley of Virginia is called the Shenandoah Valley.

From the lookout tower on Massanutten Mountain, just east of Woodstock, an excellent view of the physical features of the vicinity can be obtained. The tower is easily accessible, as a fair automobile road ascends the mountain and passes within 200 yards of it. From this vantage point on clear days the Blue Ridge and North Mountains are distinctly visible, and the observer can see for miles up and down the valley. The tower not only affords a magnificent view of the mountains and of the beautiful valley through which the North Fork of the Shenandoah flows but is also an excellent place to get a general idea of the physiography and the geology of the region.

In a general view the bounding mountains rise to a common level, which represents an ancient erosion surface. In addition to this upper surface of erosion several others can be discerned at successively lower altitudes. These were produced as the region was uplifted step by step and the streams cut deeper after each uplift. In a recent report Stose[3] has applied the name Summit peneplain to the highest erosion surface and the names Upland, Intermediate, and Valley Floor peneplains to the successively lower ones. He also describes a former flood plain of the river that is far below the Valley Floor peneplain but has been dissected by the river and now forms a series of terraces that stand about 20 feet above the normal river level.

The Valley Floor peneplain is the most conspicuous of the erosion surfaces in the vicinity of Woodstock. When viewed from a high point, such as the lookout tower mentioned above, the so-called Valley Floor appears to be a gently undulating plain that rises gradually toward the west from the river to the foot of the mountains. When the observer comes down into the valley, however, the illusion of a plain is lost, for the river and its tributaries have cut into this ancient valley floor and have converted it into a hilly country. All that remains of the original valley floor are the flat tops of some of the hills. It was upon this plain that the great meanders of the Shenandoah were developed. The river now flows at a level fully 200 feet below the Valley Floor peneplain, and its meanders are deeply

[3] Stose, G. W., and Miser, H. D., Manganese deposits of western Virginia: Virginia Geol. Survey Bull. 23, 1922.

intrenched. The intrenched meanders are a most interesting feature of the scenery and are commented on by all visitors to the lookout tower. They are so intricate that in one locality the river flows 8 miles between points which are only 1 mile apart. The harder beds in the Martinsburg shale, over which the river flows in most of its course through the region, form small but conspicuous riffles.

GEOLOGIC FORMATIONS

The rock formations exposed near the town of Woodstock range in age from Lower Cambrian to Silurian. They are listed in the table below and discussed briefly in succeeding pages. The names of formations used are those given by Stose and Miser.[4] The formations will be described from the youngest downward, which is the order in which they are encountered in drilling.

Rock formations underlying the vicinity of Woodstock, Va.

Age	Name	Estimated thickness [a]
		Feet
Silurian.	Tuscarora quartzite [b]	300
Upper Ordovician.	Juniata formation[b]	200
	Martinsburg shale	1,800
Middle Ordovician.	Chambersburg limestone	400
Lower Ordovician.	Stones River limestone	900
	Beekmantown limestone	2,300
Upper Cambrian.	Conocheague limestone	1,500
Middle Cambrian.	Elbrook formation	3,000
?	Waynesboro formation	1,250
Lower Cambrian.	Tomstown limestone	1,000
	Antietam sandstone [c]	500
	Harpers shale [c]	1,000
	Weverton sandstone [c]	100–900
	Loudoun formation [c]	0–300

[a] Thicknesses are from Virginia Geol. Survey Bull. II–A, Cement resources of Virginia, and Geologic map of Virginia.
[b] The Tuscarora and Juniata are equivalent to the "Massanutten sandstone" as described by A. C. Spencer (The geology of the Massanutten Mountain in Virginia, 1896).
[c] Not exposed near Woodstock.

The Tuscarora quartzite is about 300 feet thick and consists chiefly of well-washed and sorted quartz grains. The sand is coarse and usually cross-bedded, and there are numerous layers of pebbles. Although this formation is usually called a sandstone it is so well cemented as to be a quartzite. Owing to its resistance to erosion it

[4] Stose, G. W., and Miser, H. D., op. cit.

forms cliffs and steep slopes. It occurs on the top of Massanutten Mountain, and to its presence this mountain is due.

The Juniata formation, composed of shale and sandstone of Upper Ordovician age, lies immediately beneath the Tuscarora quartzite. In this locality the formation reaches a total thickness of about 200 feet. It consists at the top of sandstone and conglomerate which grade downward into micaceous sandy beds and then into yellow and gray shales. This lithology is in striking contrast to that exhibited farther north, where the rocks are red and about 400 feet thick. The Juniata formation is exposed on the flanks of Massanutten Mountain high above the valley.

The Martinsburg shale is a conspicuous formation in the Shenandoah Valley, being exposed on the flanks of the mountain as well as occupying a large area in the valley. Its generally gray to black color and fissile character suggested the local name "black slate." It weathers to rounded hills and gentle slopes and forms a subdued topography. The cedars that are so conspicuous on the limestone are absent on the shale. The soil of the hillsides underlain by this formation is everywhere full of small fragments of the shale, but except in steep-sided ravines and artificial excavations good exposures are uncommon. The intricate folds and the lack of exposures make it difficult to measure accurately the thickness of this shale, and estimates of its thickness range from 1,000 to 2,800 feet. It probably averages about 1,800 feet.

The Chambersburg limestone is a shaly limestone that probably does not exceed 400 feet in thickness. The conditions under which this formation was deposited were apparently transitional from those that produced the underlying pure limestone to those in which the overlying Martinsburg shale was formed. However, Bassler[5] has shown by careful study that the Chambersburg represents a distinct interval of time and is not a transitional phase of the Martinsburg shale. Because of its narrow outcrop it is of little importance as a source of water.

The Stones River limestone is the rock that crops out in the immediate vicinity of Woodstock, and the town is built largely upon it. It is about 900 feet thick in most of northern Virginia, but only about 600 feet on Pughs Run, a few miles north of Woodstock. The formation consists of relatively pure dove-colored limestone alternating with heavy-bedded dolomitic rocks. Cedars are generally common on the outcrops of this limestone, but they are not abundant in the immediate vicinity of the town.

The Beekmantown limestone, approximately 2,300 feet thick, lies beneath the Stones River limestone and consists chiefly of beds of

[5] Bassler, R. S., Maryland Geol. Survey: Cambrian and Ordovician, 1919.

pure limestone. It forms a very fertile soil, and areas which it underlies are largely cultivated. The complete and rapid weathering of the formation produces a continuous soil mantle, and good exposures are rare except in artificial cuts. A distinctive rock called "edgewise conglomerate" occurs in the upper half of the lower 500 feet of the formation, but is more common in the lower part of the underlying Conococheague limestone. "Edgewise conglomerate"[6] is composed of slender fragments of limestone tilted at all angles in a matrix of limestone distinctly different in composition. This peculiar rock has received considerable study, but its origin is not yet well understood.[7]

The Conococheague limestone, about 1,500 feet thick in this vicinity, consists almost entirely of massive dark-blue closely banded limestone. The banding is usually half an inch to 1 inch in thickness and consists of thin, wavy laminae of alternately pure and sandy limestone. On fresh fracture the banding is inconspicuous, but it weathers in relief and forms yellow raised streaks separating bands of light-blue or gray rock. Chert occurs in the lower beds and weathers out in scoriaceous masses that are much used in making stone fences.

The Elbrook formation, about 3,000 feet thick, is composed in large part of shaly limestone and calcareous shale. It weathers easily and affords few natural outcrops. The shale ranges in color from red to yellow, and the more highly colored beds occur in the lower third of the formation.

The Waynesboro formation, equivalent to the Watauga shale of southern Virginia, consists of a lower member of siliceous gray limestone and calcareous sandstone, a middle member of purer limestone, and an upper member of red and purple siliceous shale. The total thickness is estimated to be about 1,250 feet. The basal siliceous limestone weathers in such a manner that it appears to be a porous sandstone, and only in fresh cuts can its limy character be detected.

The Tomstown limestone is the oldest of the so-called "Valley limestones." It is composed largely of dolomite and limestone, in massive and thin beds, and near the base of the formation includes considerable interbedded shale. It undoubtedly underlies the Waynesboro formation in this vicinity, though it apparently does not crop out west of Woodstock owing to faulting.

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[6] Bassler, R. S., op. cit., pp. 86–88.

[7] Nason, F. L., The geological relations and the age of the St. Joseph and Potosi limestones of St. Francois County, Mo.: Am. Jour. Sci., 4th ser., vol. 12, p. 360, 1901. Bain, H. F., and Ulrich, E. O., The copper deposits of Missouri: U. S. Geol. Survey Bull. 267, p. 23, 1905. Stose, G. W., U. S. Geol. Survey, Geol. Atlas, Mercersburg-Chambersburg folio (No. 170), 1909. Brown, T. C., Notes on the origin of certain Paleozoic sediments; Jour. Geology, vol. 21, pp. 233–244, 1913. Grabau, A. W., Principles of stratigraphy, pp. 530, 784, New York, 1924.

The Antietam sandstone, Harpers shale, Weverton sandstone, and Loudoun formation, which are exposed in the Blue Ridge to the east of the area here discussed, probably underlie the area.

STRUCTURE

The rocks in this part of the Shenandoah Valley form a huge syncline that is limited on the east by the Blue Ridge and on the west by North Mountain. The syncline is cut off from the mountains by a fault of large throw, which in general parallels the axis of the valley. The simple synclinal structure is somewhat complicated by the presence of folds ranging in size from very small ones in the Martinsburg shale to large ones like those that can be seen in Massanutten Mountain. In this mountain, which extends 45 miles in a general southwesterly direction, the downfolding of the major syncline was so deep that the hard Tuscarora quartzite, which forms the resistant top of the mountain, has been preserved, though the same formation was removed from the northern part of the Shenandoah Valley, where it was more exposed. Geologic sections of this region are given in the reports by Bassler and Spencer previously cited. Figure 10 is a generalized cross section to show diagrammatically the conditions at the deep well drilled at the creamery in Woodstock and is not intended to show the details of the structure.

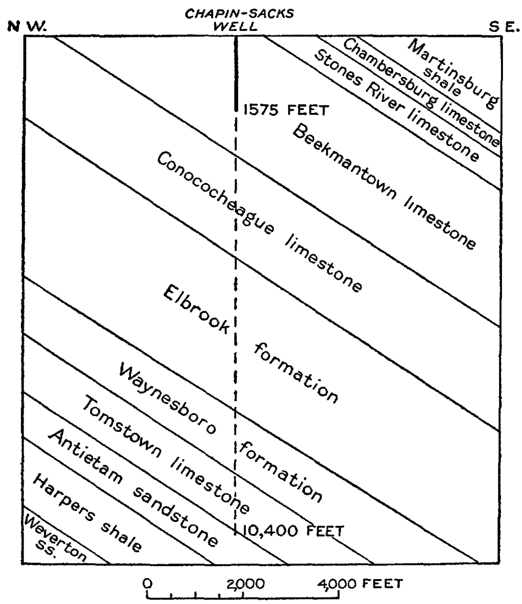

FIGURE 10.—Diagrammatic cross section of the rocks in the vicinity of the Chapin-Sacks well, Woodstock, Va.

The regional strike is N. 40°–60° E., and the dip averages between 40° and 45° SE. Locally, however, there is considerable variation in both strike and dip, particularly in the dip, which ranges from 0° to 90°. In a few localities the beds are overturned. The greatest changes in dip within a short distance are observable in the Martinsburg shale.

One major fault lies along the western edge of the valley, approximately parallel with the regional strike, but there are some minor faults that trend almost at right angles to it. The major fault has a throw of several thousand feet, but as a rule the minor faults have throws not exceeding a few hundred feet. As a whole the rocks in the vicinity of Woodstock appear to be less complexly faulted than the rocks of similar age and type in areas both to the north and to the south.

WATER-BEARING PROPERTIES OF THE ROCKS

Ground water occurs in the vicinity of Woodstock chiefly in shale and limestone of Ordovician age, and the following discussion will be divided into two parts, based on the type of rock in which the water occurs. The shale formations are the Juniata and Martinsburg, and the limestone formations are the Chambersburg, Stones River, and Beekmantown.

SHALE FORMATIONS

The Martinsburg shale, locally called the "black slate," forms a strip of variable width along the east side of the valley, as shown in Plate 7. Although the shale itself is alomst impermeable, it contains numerous open bedding planes and joints in which is stored much water that is available to wells. In dry seasons, however, the amount of stored water is very much reduced, so that wells and springs diminish in their yield and frequently go dry during prolonged droughts. This is especially true of many of the shallow dug wells.

The municipal water supply of Woodstock is in part[7a] derived from five hillside springs that are fed by the water stored in the joints of the Martinsburg shale. During periods of dry weather, when this store of water is not replenished, the flow of these springs is always reduced, and one or two of them are reported to cease flowing during prolonged droughts. In the dry year 1920 an effort was made to augment the quantity of water by drilling a well 217 feet into the shale. Water was encountered at 100 and 150 feet below the surface and rose to a level 30 feet below the surface. When the well had been completed by the driller it yielded on test between 40 and 50 gallons a minute. In order to avoid the cost of pumping a tunnel was driven from the lower reservoir, a distance of 80 feet, to the well at a level low enough to divert the water as it rose in the well. When the writer visited the locality on July 22, 1924, the flow through the tunnel was about 5 gallons a minute. It is reported that the flow was considerably less than that during the summer of 1923, although it did not cease entirely.

[7a] Since this was written Woodstock has obtained an additional supply from Little Stony Creek.

Drilled wells in the Martinsburg shale usually have small but satisfactory yields, as shown in the examples herewith described. A drilled well on the property of Mrs. W. E. McInturff, a quarter of a mile east of Maurertown, is 75 feet deep and yields 5 gallons a minute. The water, which rises within 25 feet of the surface, is used for domestic purposes. The well on the property of Mr. W. E. Boyer, also near Maurertown, is 105 feet deep and yields 4 gallons a minute; the water in the well rises within 11 feet of the surface. The owner uses the well only as a reserve supply, preferring cistern water because it is softer, but he reports that the well water has no objectionable features except that it is hard. As shown in the analysis on page 65, the water contains 508 parts per million of total dissolved solids, and its hardness is 380 parts per million. Its temperature on October 11, 1924, was 56° F. The well of Mr. C. Brenner, 1 mile east of Woodstock, is 103 feet deep, ends in the Martinsburg shale, and yields several gallons of water a minute. The water is used for domestic purposes.

Wells in the Martinsburg shale rarely exceed 150 feet in depth. They generally obtain yields of a few gallons a minute but rarely more than 15 gallons a minute. The well water is generally used for drinking and is considered by the users as good but hard. Many well owners supplement their hard well water supply with rain water that is collected on the roofs of the buildings and is stored in cisterns. The soft cistern water is used chiefly for washing.

LIMESTONE FORMATIONS

The limestones of the area were formerly grouped as the Shenandoah limestone, but recent detailed work has made it possible to recognize a number of different formations distinguishable on both paleontologic and lithologic grounds, and these formations are listed on page 52. However, the differences in lithology among the limestone formations are not great enough to produce much difference in their water-bearing properties, and hence for the purposes of this report they can all be considered under one heading. The available data on ground water in this area pertain largely to the Stones River and Beekmantown limestones, but these data can be applied to all the limestones. Although the Elbrook and Waynesboro formations contain considerable shale and sandstone, they are, when unweathered, fairly calcareous and doubtless closely resemble the other limestone formations in their water-bearing properties. The Lower Cambrian sandstone and shale are not exposed in this area and their water-bearing characteristics are not discussed.

Compact limestone, such as occurs in the Shenandoah Valley, is a nearly impervious rock. Water can not flow freely through the solid rock nor be stored in it. However, where the rock is fractured or creviced wells in it may have large yields. The openings in the limestone consist of joints and partings along bedding planes and of much larger openings due to solution along the joints and partings. The joints in limestone, like those in other rocks, are largely the result of breaking under pressure, probably during the folding of the rocks of the region. Solution channels are characteristic only of limestone, gypsum, and salt and are due to the dissolving of the rock material by ground water. In humid regions, such as the Shenandoah Valley, there is in normal years sufficient precipitation to furnish plenty of ground water, which, when charged with carbon dioxide, dissolves limestone. A very small percentage of carbon dioxide is absorbed from the air by the rain, but the amount is sufficient to make the water a solvent for limestone. Additional carbon dioxide is doubtless absorbed in the passage of rain water through the soil where vegetation is decaying. The process of solution of limestone is open to inspection in the many caves in the valley. The rooms and passages in caves are solution channels once occupied by ground water but now generally above the water table, though in wet seasons small quantities of water find their way through the caves. The channels vary greatly in length and size. Some give rise to springs, but others are dry or partly filled with mud. Most of the successful limestone wells obtain their water from solution channels that are encountered at about the level of the North Fork of Shenandoah River, but in some wells the water rises above the level at which it is encountered, indicating that the water circulates in these channels under some pressure.

In this region the solution channels probably do not extend to great depths below the water table. The solution of limestone depends on the circulation of water containing carbon dioxide. As the ground water passes along the solution channels it dissolves some rock, but this process continues only so long as there is carbon dioxide in the water. As the total amount of carbon dioxide in solution is generally small, most of it is used up before the water percolates very far. A short distance below the water table the water is nearly devoid of carbon dioxide, and, moreover, it circulates only very slowly, and therefore the rock is not dissolved away or is dissolved at a slow rate. Not only is the solution of rock arrested below the water table but deposition of mineral matter may take place, as is attested by the innumerable tiny veins that occur throughout the limestones.

There has been intense folding and faulting in the Appalachian province, as a result of which the rocks were broken and in places more or less crushed, but these fissures may have generally been recemented with calcite below the water table. Careful examination of outcrops reveals many calcite veins, most of which fill openings caused by earth movements. These veins vary in size from half an inch down to microscopic width and are present in all the limestones, although most conspicuous in the darker ones on account of the difference in color. In some places, however, fault and joint planes are probably still open, and some solution channels may occur at considerable depths below the water table. However, the Chapin-Sacks well, which was drilled to a depth of 1,550 feet and obtained little or no water below 200 feet, evidently did not encounter such deep openings.

Although the greater part of the foregoing discussion has concerned itself with the large openings, small ones also occur, and when encountered in sufficient number they yield fairly large quantities of water, like the small openings in the Martinsburg shale. The formation of only small openings at any place is due either to the short time that water has circulated at that place or to the existence of less soluble portions of the limestone beds between the numerous small openings.

The physiographic history of the region is one of periodic uplift with intervals of erosion. At no time does there appear to have been any appreciable subsidence that would have submerged the solution channels far below the water table. The general regional movement has always been upward, resulting in rejuvenation of the streams and erosion of the uplands. Thus there has been a constant lowering of the solution channels and of the water table. The height of the water table varies considerably with the season and from year to year, as is shown by the difference in level of water in wells in 1923 and 1924, but this range in level is a matter of only a few feet, whereas the changes in altitude of the water table due to the uplifts of the region are measured in hundreds of feet.

In pioneer days, when settlers first entered this fertile limestone valley, streams and springs furnished an adequate supply of pure water, but the streams soon became polluted, and as settlement increased there were not enough springs to furnish water for every household, nor were they all conveniently located. Consequently shallow wells were dug, many of them more than a century ago. At present dug wells are largely out of favor, and many have been replaced by drilled wells. Dug wells are being abandoned partly because they are more likely than drilled wells to go dry during a drought and also because it is difficult to keep them from becoming contaminated. Most dug wells do not reach far below the water table, and when the water table is lowered by a drought the well becomes dry. At such times a well may have to be dug deeper, but the deepening of a dug well is an expensive and hazardous task. Dug wells are usually not carefully cased, and surface filth and small burrowing animals are not excluded. Even where care is taken to cover the wells, the platforms may not be tight, and water spilt on them carries the accumulated filth into the well. Polluted drinking water may cause serious illness, involving loss of time and expensive medical attention. Consequently dug wells, though low in initial outlay, may prove to be very costly in the end. In Woodstock, where a municipal water supply has been available for more than a quarter of a century, nearly all the dug wells have wisely been abandoned, but in the surrounding country many dug wells are still in use.

The dug well in Spring Street, just east of Main Street, differs from most dug wells in that it normally overflows at the surface. It had been little used for a number of years. During the drought in 1923 this well ceased flowing, but on account of the need for water that year the Chapin-Sacks Corporation had the well cleaned out, installed a centrifugal pump direct connected with a 25-horsepower electric motor, and laid about half a mile of 6-inch pipe to the creamery. When the rubbish that had accumulated in the well was removed the workmen found that the well is about 48 feet deep and that two natural tunnels at the bottom lead off to the west and northwest. These tunnels are solution channels in the limestone and through them the water enters the well. During the summer of 1923 the yield was small, and the water did not rise at any time more than 6 feet above the bottom of the well. The yield was so small that on pumping at the rate of 200 gallons a minute the supply was soon exhausted, and it was necessary to wait several hours before the water again reached the depth of 6 feet. In the winter of 1923 the water level in the well rose rapidly, and by May, 1924, the well again overflowed. Since May the well has overflowed at the rate of 25 gallons a minute, and the water level inside the well is about 18 inches above the overflow pipe. It is reported that on pumping with the equipment previously used the drawdown after a period of several hours of pumping is less than 6 inches and the natural overflow is not greatly decreased. The water from this well is polluted, and the State health department has forbidden its use for human consumption, but as its temperature is only 55° F. it is useful for cooling. As shown in the analysis on page 65, the water contains 381 parts per million of total dissolved solids, and its hardness is 342 parts per million.

Drilled wells are numerous throughout the area and reliable information concerning them is available. Information concerning 30 drilled wells was obtained. These wells range in depth from 111 to 1,550 feet, the depth at which water was encountered from 40 to 565 feet, the level of the water below the surface from 11 to 80 feet, and the yield from 5 to 60 gallons a minute. All these wells are within

5 miles of Woodstock, except the well at Stephens City, approximately 20 miles northeast of Woodstock.

The new well at the Chapin-Sacks creamery, at the northwestern edge of Woodstock, is 1,550 feet deep and is one of the deepest if not the deepest well in this part of the Shenandoah Valley. This well yields about 60 gallons a minute with a 300-foot draw down. It starts near the top of the Beekmantown limestone and ends in the same formation, as shown in Figure 10. The well obtains all of its water in the first 250 feet. The first water was encountered at 188 feet and rose to a level 55 feet below the surface; the second was found at about 250 feet and rose to a level 42 feet below the surface. The drillers report that they did not encounter any large openings while drilling this well and that below the 250-foot level there was no indication of any additional water. This water contains 339 parts per million of total dissolved solids, and its hardness is 314 parts per million. In the same lot are two drilled wells, 180 feet and 240 feet. The 180-foot well yielded only 15 to 20 gallons a minute, mostly from a depth of 80 feet, and is now abandoned. The 240-foot well yields about 35 gallons a minute, and most of the water also comes from a depth of approximately 80 feet. This water contains 397 parts per million of total dissolved solids, and its hardness is 316 parts per million. When these wells are pumped simultaneously the yield of each is decreased, and this fact is taken to mean that they draw from the same source, but in neither well were any large openings in the rock reported by the drillers.

The other wells in the vicinity of Woodstock are similar in that they penetrate rather solid limestone with few if any large openings. The abandoned well at the foundry, drilled about 1880, is reported to have been 112 feet deep and to have had a small yield. The well on the property of the Standard Oil Co. is 153 feet deep. The water enters the well about 75 feet below the surface and rises to a level 40 feet below the surface. The well of M. B. Wonder, about a quarter of a mile north of the Standard Oil Co. well, is 220 feet deep and yields about 5 gallons a minute. The water enters the well about 180 feet below the surface. The two wells at the abandoned creamery on the east side of the town were 158 and 300 feet deep, and both were in the Stones River limestone. The 300-foot well yielded on test about 12.5 gallons a minute and the 158-foot well somewhat less. Both wells are reported to obtain most of their water about 100 feet below the surface. The drillers did not encounter any large openings in the rock.

To the south and west of Woodstock, in the general neighborhood of the fair grounds, there are several wells drilled into the Beekmantown limestone. The well on the fair grounds is 165 feet deep and the water stands 60 feet below the surface. The drillers report that they found an opening in the rock from 160 to 165 feet below the surface. A large quantity of water can probably be obtained from this opening, but the well has never been thoroughly tested. The pump now installed obtains about 10 gallons a minute with a small draw down. The well of M. L. Walton is 215 feet deep and yields approximately 14 gallons a minute. The water enters the well in three places between 80 and 215 feet. The well of H. C. Stauffer is 120 feet deep and encountered water at 85, 95, and 115 feet. The drillers do not report any large openings but mention small crevices. The water rises within 70 feet of the surface and the well yields about 15 gallons a minute. The well of J. G. Gravely, some distance from the fair grounds, is discussed on pages 46 to 49. The water contains 360 parts per million total dissolved solids and its hardness is 251 parts per million. The well of E. Homer Artz, just south of the town, is 123 feet deep and yields about 16 gallons a minute.

In sharp contrast to the uniformly compact rock encountered in wells at the creamery the well drilled in the Stones River limestone by William J. Gochenour for his filling station at Maurertown encountered a large opening at a depth of 103 feet. The drill tools dropped into this hole a distance of 5 feet, and water rushed into the well and rose within 27 feet of the surface. During a three-hour test the well was pumped at the rate of 17 gallons a minute, and the draw down was only 7 feet. The same owner has another well in the Stones River limestone about a mile farther south, which is 209 feet deep, obtains most of its water from a depth of 80 feet, and yields about 4 gallons a minute. The water level is 79 feet below the surface, and therefore the water is under almost no artesian pressure. Another well near by penetrates first the Martinsburg shale, but obtains its water from the Chambersburg limestone at a lower level. The well is 163 feet deep, has a water level within 50 feet of the surface, and yields only a few gallons a minute. Near these three wells, on the farm of William J. Gochenour, is a well in which several water horizons in the Stones River limestone were encountered, but no large openings were reported. The total depth of this well is 365 feet, but all the water was obtained in the first 250 feet. The water stands within 60 feet of the surface, but during a 65-minute test when 20 gallons a minute was pumped the drawdown was 170 feet.

From the detailed description of wells in limestone given in the foregoing paragraphs and a consideration of the general principles underlying the formation of solution channels in limestone (p. 58), the conclusion can be reached that the success or failure of a well is dependent on striking crevices that carry water. Underground channels filled with mud, which flows into the hole and delays the drilling, are found in some wells, but most of these channels are either above the water table and dry or below it and full of water. They are distributed in a most irregular manner throughout the body of rock, and it is a matter of chance whether in a particular locality one will be encountered. Those wells that strike one large channel with a large volume of water or several smaller ones containing in the aggregate a considerable volume will yield large quantities of water; those which encounter only a few small openings will yield only a small supply. Wells drilled into solid rock without cavities are usually failures. The limestone has an enormous number of small openings, and wells usually encounter enough of them to yield sufficient water for ordinary farm use. Channels of large volume, however, are not numerous and are found so seldom that wells yielding more than 50 gallons a minute are uncommon. All but one of the wells near Woodstock encounter water above a depth of 300 feet, and the only well drilled to a greater depth was dry below 300 feet. It is therefore recommended that in drilling wells a dry hole be abandoned when it has reached a depth of 300 feet and another well be put down at a new location.

The cost of reaching the underlying sandstones that might contain water is prohibitive in this locality because of the great depth at which they occur. As shown in Figure 10, the depth to the Antietam sandstone is probably not less than 8,000 feet anywhere in the immediate vicinity of Woodstock. Not only would an attempt to obtain water from this formation be excessively costly, but it might end in failure, both because of the difficulties of drilling so deep a well and because the pores of the sandstone may be filled with mineral matter at so great a depth and the rock may therefore be dry.

CHEMICAL CHARACTER OF THE GROUND WATER

Six samples of water from wells in or near Woodstock were analyzed and show a range in total dissolved solids of 223 to 508 parts per million, and a range in hardness from 186 to 380 parts per million. These waters, which may be considered characteristic of the area, are thus relatively high in total dissolved solids and have a rather high hardness. However, this hardness is almost entirely carbonate hardness except in the sample of water from the Martinsburg shale, in which the noncarbonate hardness is rather large compared to that in the samples from the limestone, being eleven times greater than in No. 2 and six and one-half times greater than the average of Nos. 2 to 6.

As shown by the table of analyses on page 65 and more graphically by Figure 11, calcium is the preponderant base in all but one sample, magnesium is next in amount, and the contents of sodium and potassium are relatively small. The four analyses given last in Figure 11 represent waters derived from the more dolomitic rocks. Larger amounts of magnesium should be expected in water from such rocks, and in sample No. 6 magnesium is the chief base. This water also

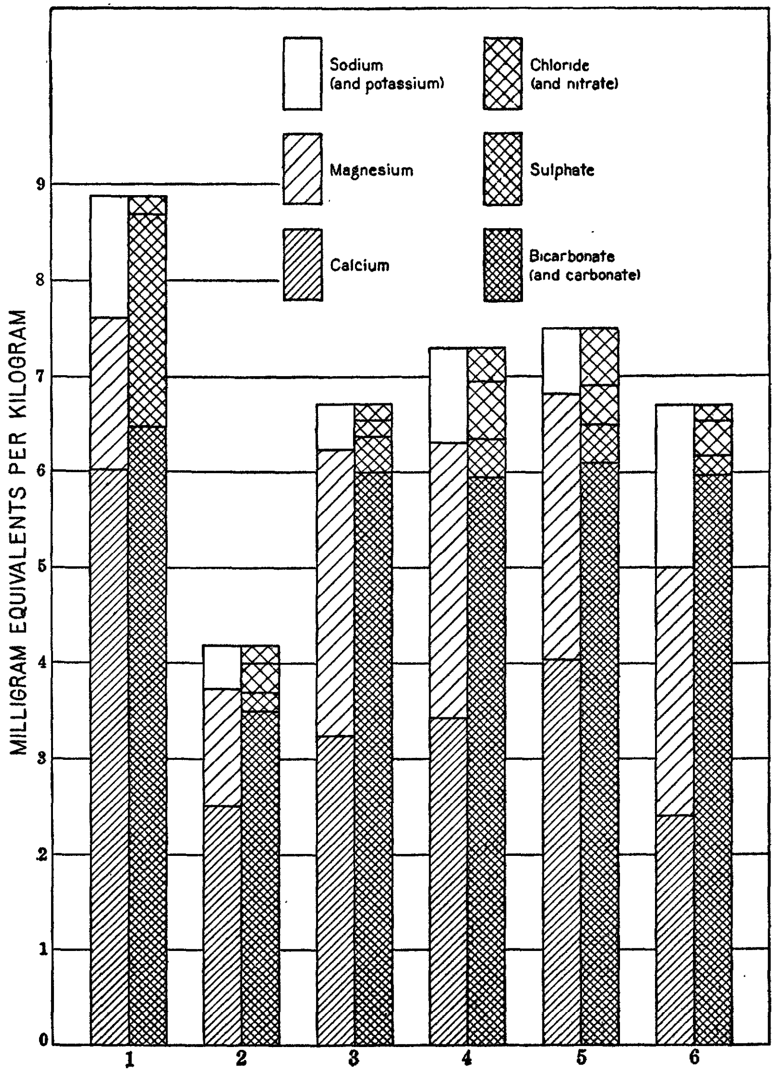

FIGURE 11.—Graphic representation of analyses of well waters from vicinity of Woodstock, Va.

has a sodium and potassium content exceeding that of any other sample.

The bicarbonate radicle is the preponderant radicle in these samples. The quantity of sulphate is small in all samples except in the water from the Martinsburg shale. Both chloride and nitrate are small in amount, though nitrate is rather high as compared to the amount in many other waters.

These waters are suitable for all domestic purposes except that they are rather hard for washing. On many of the farms there are cisterns for catching rain water for laundry and toilet uses. Cisterns are much more common on the Martinsburg shale areas than on the limestone, probably owing to the greater permanent hardness of the well water.

The value of the ground water in this area for industrial use is greatly lessened by the presence of the relatively large amounts of scale-forming constituents. However, where it is necessary to use these waters in boilers, they can be treated successfully by softening systems or with suitable boiler compounds. The ground water, when obtainable in sufficient quantities, is valuable for use in cooling, as it has an average temperature of only about 55° F.

Analyses of well waters near Woodstock, Va.

[Collected October 10-12, 1924. Analyzed by H. B. Riffenburg. Parts per million]

	1	2	3	4	5	6
Silica (SiO_2)	18	4.8	12	11	9.4	10
Iron (Fe)	1.2	3.6	1.3	.60	.13	.40
Calcium (Ca)	121	50	65	69	81	48
Magnesium (Mg)	19	15	37	35	34	32
Sodium (Na)	28	9.4	8.9	19	13	40
Potassium (K)	1.4	1.8	2.2	6.0	5.2	3.1
Bicarbonate radicle (HCO_3)	395	215	366	361	354	359
Sulphate radicle (SO_4)	107	10	18	19	20	11
Chloride radicle (Cl)	7.0	9.0	5.0	18	16	13
Nitrate radicle (NO_3)	Trace.	12	11	22	36	9.6
Total dissolved solids at 180° C	508	223	339	397	381	360
Total hardness as $CaCO_3$ (calculated)	380	186	314	316	342	251

1. Drilled well 105 feet deep; water from Martinsburg shale; owned by J. E. Boyer, Maurertown, Va.
2. Drilled well 108 feet deep; water from Stones River limestone; owned by Wm. J. Gochenour, Maurertown, Va.
3. Drilled well 1,550 feet deep; water from upper 250 feet, from Beekmantown limestone; owned by Chapin-Sacks Corporation, Woodstock, Va.
4. Drilled well 240 feet deep; water from Beekmantown limestone; owned by Chapin-Sacks Corporation, Woodstock, Va.
5. Dug well 48 feet deep; water from Stones River limestone; owned by town of Woodstock, Va.
6. Drilled well 181 feet deep; water from Beekmantown (?) limestone; owned by J. G. Gravely, 1 mile west of Woodstock, Va.

POLLUTION OF THE GROUND WATER

The large number of sink holes in this vicinity is a feature immediately noticed by even the casual visitor. A single field may contain several of them. Streams are scarce, the run-off is small, and much of the surface drainage leads into the sink holes; hence a large part of the precipitation becomes ground water. These sink holes are the starting points of the numerous solution channels that furnish the supplies to the wells and springs. That some springs and wells are closely connected with sink holes is shown by the fact that their water becomes muddy during a rainy period, in some of them within a few hours after a heavy shower. Obviously, wells and springs so directly connected with the surface may easily become polluted, especially where the sink holes are used as dumping grounds for refuse and where abandoned wells are used as cesspools.

The Chapin-Sacks Corporation had been turning its creamery waste into an open ditch, which became very foul. To get rid of this waste a sewer line about half a mile long was constructed, which ended in a sink hole in a field opposite the Standard Oil Co.'s plant. The first sewage was dumped in the sink hole in July, 1919, and within less than 48 hours afterwards milky water began to issue from the spring of Carl Gill, near the mouth of Pughs Run, about 1.5 miles away. The surrounding rocks soon turned black, the water had a foul odor, and the spring was ruined. To get rid of this objectionable water the spring was inclosed and the foul water was piped to the river. This spring is reported to have muddied up quickly during rainy periods, showing its close connection with the sink hole. A well was drilled within 100 yards of this spring to supply the property owner with water. This well is 234 feet deep and yields 10 gallons a minute. The water was encountered at 120 and 220 feet and rises within 80 feet of the surface. Although relatively close to the spring, this well apparently did not encounter the solution channels that supply the spring.

CONCLUSIONS

1. In the vicinity of Woodstock drilled wells are preferable to dug wells, because they are more sanitary and less likely to go dry.

2. In the shale area drilled wells less than 200 feet deep will generally yield supplies of hard water sufficient in quantity for farm use, but large supplies can rarely be obtained from the shale.

3. The yield of wells in the limestone area is variable and depends on the size and number of water-bearing crevices that are encountered in drilling.

4. In general it is not advisable to drill deeper than about 300 feet in either shale or limestone. If a drill hole is still dry at this depth it should be abandoned and a new location should be sought.

5. Wells in limestone are subject to pollution not only from near-by sources but also from contamination that enters the ground water through distant sink holes. On the other hand, wells in the Martinsburg shale are not likely to be contaminated except by near-by filth. The practice of dumping waste into sink holes and discharging sewage into abandoned wells or holes drilled into cavernous limestone should be discontinued.