Evaluation of Yields of Wells in Consolidated Rocks, Virginia to Maine

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2021

Prepared in cooperation with the U.S. Army Corps of Engineers

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By D. J. CEDERSTROM

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A new approach to an old problem

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EVALUATION OF YIELDS OF WELLS IN CONSOLIDATED ROCKS, VIRGINIA TO MAINE

By D. J. Cederstrom

ABSTRACT

In the North Atlantic region, Virginia to Maine, yields of industrial and municipal wells are the most reliable indicators of the water-yielding potential of consolidated rocks. Generally, such wells represent efforts to develop a maximum supply of water, they are 350 to 500 feet deep, and they utilize 60 to 150 feet of drawdown. In multiple-well developments, average yields of wells per 100 feet of drawdown range from less than 75 gallons per minute in the least favorable rocks such as shale or granite gneiss to as much as 300 gallons per minute in limestone. In any one rock type, substantially greater than average sustained yields are possible in structurally deformed areas or in areas where recharge potential is especially favorable.

INTRODUCTION

It is a reasonably defensible statement that the yield of an individual well in consolidated rocks cannot be predicted accurately. However, the average yield to be obtained from a group of wells can be estimated reasonably well where sufficient data on existing wells are at hand. The adequacy of the estimate will depend largely on the completeness of data available and on the experience and judgment of the evaluator.

Wells drilled in consolidated formations are located in a great variety of physical situations. They may be deep or shallow, and few of them, if any, are developed in the manner screened wells are developed in unconsolidated formations. As a result, whether the yield of any one well will be a few gallons a minute or several hundred gallons a minute cannot be predicted with confidence. Nevertheless, in the last few years the hydrologist's task has been to state categorically that the average yield of wells in various hard-rock formations is a certain number of gallons a minute. In dealing with this difficult problem it must be understood clearly that the estimate arrived at in such a study cannot refer to the yield of a single well but rather to the average yield per well where a number of wells is considered. The minimum number of wells is conveniently taken as five because, where water for future municipal or industrial developments is needed in hard-rock areas, the number of wells drilled for any one development will commonly equal or exceed five.

This paper deals with the methods used in evaluating the average yield of multiple wells in consolidated formations where a maximum supply of water is desired. As noted, the estimates arrived at refer to the average yield of five wells drilled in the formation. Furthermore, it is assumed that the well sites will be chosen by a ground-water hydrologist who will select optimum locations, or who will at least insure that wells are spaced widely enough to encompass favorable sites as well as what may be unfavorable sites. The suggestions made and guidelines given here for evaluating yields are not necessarily hard-and-fast rules; they are, rather, methods which the writer has used in his evaluations, based on his own thinking as well as the comments of several hydrologists who have also worked in hard-rock areas. At our present stage of knowledge, this somewhat vexing problem of yields of wells in hard-rock areas can be dealt with intelligently, but it cannot be resolved to yield absolute conclusions.

Records of tens of thousands of wells penetrating granite and other crystalline rocks, indurated sediments, and metamorphic rocks seemingly show that consolidated rocks generally yield small quantities of water. However, most of these wells are domestic wells that are intended to produce only a small amount of water at a minimum depth. The data, therefore, conspicuously fail to show what the yield might be if efforts were made to obtain maximum supplies. As given in most reports, the average yield of wells drilled in the various hard-rock formations is, therefore, of little value in assessing the full potential of the rock formations.

To obtain a maximum supply, wells must be located where geologic and hydrologic conditions are thought to be most favorable in a considerable area (perhaps 2 or 3 sq. mi.); the wells must generally be drilled to depths of 400 to 500 feet; they should be developed by conventional means; and much of the available drawdown must be used in pumping the well. Whether many or few of the tens of thousands of wells listed in published inventories meet all or most of these conditions is most difficult to determine. Many or, perhaps, most of the wells used in the evaluation of maximum yields arrived at here were located on the basis of convenience rather than where conditions were thought to be favorable. Hence, estimates made probably are somewhat conservative.

PURPOSE

The purpose of this report is to show the average yields that may be expected of deep wells in the North Atlantic region in consolidated rocks where five or more wells are drilled, at sites selected by a hydrologist, and where about 100 feet of drawdown is used.

Data are insufficient in many areas to arrive at valid yields by simple averaging. The methodology followed in dealing with such data is discussed with the intent of providing a guide to other investigators and to supplement, verify, or question yields arrived at elsewhere. Departures from average yields, particularly yields two or three times the average yield as given here, are pointed out in order to emphasize certain critical factors that may be used to advantage by future developers.

ACKNOWLEDGMENTS

The following paper is a byproduct of the North Atlantic Regional Water Resources Study, a multidiscipline project carried out under the leadership of the U.S. Army Corps of Engineers. The writer, as a U.S. Geological Survey participant in that study, was directed to prepare a discussion of ground-water availability in the study area. A desirable goal was to make as thorough a study of the yields of wells in consolidated rocks as time would permit. An average figure on the yield per well in various environments was needed, first, to show, the number of wells that would be needed to produce the estimated available water and, second, to evaluate the cost of the well installations. This report describes the methodology employed in estimating well yields in the study, specifically yields of wells in the North Atlantic region, Virginia to Maine, but the reasoning used here may be applicable to evaluations in other areas.

Appreciation is expressed to numerous colleagues for time they have given in informal discussion of ideas presented.

FACTORS INFLUENCING ESTIMATES OF YIELDS OF WELLS

DISTRIBUTION OF WELL SITES

The average yield based on arithmetic or other plotting of all wells may not yield a representative average because the wells are commonly clustered in relatively few sites. Hence, they may be situated largely in unfavorable areas, or largely in better-than-average areas. For instance, in some areas most wells may be located on high ground underlain by massive rock, generally a less favorable site. Commonly, most of the useful data may be clustered around an industrial complex representing only a tiny fraction of the total area of the formation being considered. In New England most wells on which averages are based are located on low ground, which may represent fracture zones and where recharge from overlying glacial sands is possible. In some areas of Pennsylvania, few wells are found on sandstone ridges. Sandstones there may appear to be poorer aquifers than they really are.

GEOLOGIC FACTORS

Certain rocks are characteristically "tight"; that is, they lack open space for the storage of water and channels for transmitting the available water to a well. Only very low yields may be expected from shales or shaly formations. On the other hand, limestones in the northeastern region are commonly replete with openings and many yield water freely to wells. Sandstone is a moderately good aquifer. The crystalline rocks, such as granite and schist, are poor aquifers, although they are somewhat better than shale.

For more than two decades, fissure and fracture zones (commonly marked by subordinate valleys) in crystalline-rock areas have been known to be favorable well locations (Mundorff, 1948; Baker, 1957). Vegetative or other patterns discernible on aerial photographs may indicate the presence of these fractures or zones of fractures that are especially favorable well locations in limestone rocks (Lattman and Parizek, 1964; Parizek and Drew, 1966; Trainer and Ellison, 1967). In a study of yields of wells in sandstone, Widmer (1963) points out that in the Trenton, N.J., area 87 percent of the successful industrial wells in Triassic sandstones is located on linear topographic features, whereas only three out of 13 unsuccessful wells are located on linear features.

Contact zones between large resistant masses of rock and less stable adjacent formations may prove to be loci of fissuring during gentle earth movements and thus favorable sites for wells. Where large rock units have moved relative to one another along major faults, zones of fracture and minor faulting will commonly be present along the faults, and yields of wells may be particularly high there. Later enlargement of fractures by solution occurs in some rocks and thus further increases the permeability of the rock. However, many fault zones have been rendered relatively impermeable by the creation of gouge (fine granulated or powdered rock) along planes of movement. Simmons, Grossman, and Heath (1961) describe a well in a fault zone in southeastern New York State (city of Beacon) that penetrated nearly 300 feet of disintegrated limestone mixed with clay. It was stated that this material yielded water freely, but the bedrock was very soft and caved continuously when the well was pumped.

Therefore fault zones may or may not mark favorable well sites.

The rocks in the entire North Atlantic region have undergone such structural deformation during several periods of mountain building that the rocks have been rendered more permeable than in some other region. Thus, the yields of wells in rocks in the Appalachian Valley are seemingly greater than those in the Appalachian Plateaus area (Wyrick, 1968), particularly where folding and faulting have been intense (pl. 2). Wells having yields higher than the average (see table 1) are often located along major faults such as the western border fault in the Triassic formations and faults in the eastern part of the Appalachian Valley. Other exceptionally high-yield wells are located in areas of intense folding. The lack of such wells in many areas of structural deformation is no indication that higher-than-average yields may not be available. Rather, the absence of exceptionally high-yield wells is almost certainly due to the general availability of streams and spring waters and to the lack of effort by industries and municipalities to develop large quantities of ground water.

DRAWDOWN

Another highly important factor to be considered in an evaluation of well records is the drawdown in the well at a stated yield. Very commonly the discharge of a well increases with an increase of drawdown. If an evaluation is to be made for cost-planning purposes, then a uniform drawdown comparable to that used in many industrial and municipal wells must be assumed. In the study of records of wells from Maine to Virginia, yields at 100 feet of drawdown were sought. The yield of a well in granite in Richmond, Va., 300 gpm (gallons per minute) (Sanford, 1913), is not so spectacular as it might otherwise seem because the pump intake is set at a depth of 300 feet below the water table, so that presumably considerable drawdown was used. With an arbitrary standard of 100 feet of drawdown, the yield would probably be less. Conversely, if a well has a stated yield with only 15 feet of drawdown, the yield with 100 feet of drawdown will generally be greater.

What is the relation between yield and drawdown in wells in hard-rock areas? A general answer to that question does not exist. One assumption is that for nearly all wells the yield will increase with increase of drawdown, but the amount of increase is problematical. If a well yields 20 gpm with 10 feet of drawdown (specific capacity of 2), it does not follow that with 100 feet of drawdown, the yield will be almost 200 gpm. Data showing the decrease of specific capacity (that is, decrease of yield in gallons per minute per foot of drawdown) with increase of drawdown in rock wells are extremely meager. Hence,

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where a record shows that only a small part of the available drawdown was used at a certain discharge, projection of yield utilizing 100 feet of drawdown must be attempted with extreme caution.

Wells in hard rocks yield water from joints, fissures, bedding planes, and solution channels. These may or may not occur along the entire length of the hole. However, to illustrate the possible effect of increasing the drawdown in a rock well, let us assume that one fissure or tube is intersected by the well and that static water level is 10 feet above that intersection. When the water level is lowered by pumping, the yield increases proportionately until the water level reaches the level of the fissure or tube. However, when the water level (increase of drawdown) is lowered below the fissure or tube, there is no increase in yield whatsoever.

Considering that the fissures or other openings intersected by a hole in a rock mass may be few or many, horizontal or inclined, and wide or narrow and that they decrease regularly or irregularly in number per unit of depth, neither a rule of thumb nor a scientific approach, either mathematical or statistical, will likely ever result in a generally applicable equation or graph showing the decrease in specific capacity with progressive increase in drawdown. If a great many graphs showing decrease of specific capacity with increase of drawdown (the familiar step-drawdown test) were available for rock wells, one inference might be (quite possibly incorrect) that in a certain area a well in a certain type of rock formation would generally decrease in specific capacity with increase of drawdown. Where 5 gallons per foot of drawdown was obtained by utilizing a certain percentage of available drawdown, specific capacity might decrease to 3 at double the previous drawdown, and so on. There would be many exceptions to any such role decided upon, but having a large number of rock-well performance records at hand would at least narrow the area of ignorance somewhat.

Developers should keep in mind that although increasing the drawdown in any one well may result in no gain or negligible gain in yield, increasing the drawdown in a group of widely spaced wells will, with rare exception, result in an appreciable overall increase in yield.

A yield of 200 gpm from a well in rock other than limestone or dolomite, but with large drawdown, suggests the presence of many fractures, each one yielding a little water, throughout the full length of the wall bore. In such a well the decrease in yield associated with a decrease in drawdown from 200 to 100 feet may be substantially less than 50 percent. A valid assumption is that a well yielding 200 gpm at 200 feet of drawdown will yield about 133 gpm at 100 feet of drawdown.

A well tested with only 10 feet of drawdown may decline greatly in specific capacity when drawdown is increased from 10 to 100 feet. Where discharges were given at very small drawdown the well data were not used in the calculations. Fortunately, few wells are tested with as little as 10 feet of drawdown, and estimates of yield are commonly based on pumping performance where reported drawdown is near or in excess of 100 feet.

Meisler (1963) lists the specific capacities of several wells in limestone. These determinations range from 1 to 264 gpm per foot of drawdown. However, these values were determined by pumping at a rate of 10 to 15 gpm for 1 hour. Projection of such data to higher yields at proportionate drawdown under continuous pumping conditions would be invalid. The best that might be said about such data is that they suggest that some high yields could probably be obtained from place to place in the area.

Brief mention should be made of bailing tests even though they were not relied on in the evaluations made in this report. Bailing tests fall into much the same category as wells tested utilizing minimum drawdown, although some bailing tests are made at discharges of 40 to 50 gpm. A half-hour bailing test that shows a yield of a few gallons a minute at a drawdown of 140 feet is useful for evaluations—the well is a very poor one, and it makes little difference in the averages if the yield is listed at 1 or 3 gpm. However, a reported yield of 40 gpm at 30 feet of drawdown, in a brief bailing test, should not be ignored but is very hard to use properly. Should it be accepted as 40 gpm at 30 feet of drawdown or as half that yield at the same drawdown under continuous pumping conditions? Furthermore, the yield at 100 feet of drawdown cannot be evaluated.

Many county reports cover rural areas where almost all wells are domestic wells and where yields, if given at all, are unaccompanied by corresponding drawdown data. Such records are of little worth in evaluating the potential of the formations present. About the most that might be gained is an impression that a maximum of 10 or 20 gpm can be obtained from somewhat shallow wells and that the formation looks good with respect to obtaining 50 or 100 (or more) gpm. Or conversely, if only very low yields are reported and if wells seem to be located in a variety of sites (in both the presumably favorable as well as the presumably unfavorable sites) and are of at least moderate depth, the formation would probably not yield more than an average of 10 to 15 gpm per well at 100 feet of drawdown.

In some lists of domestic-well records, a few drawdown data are given. This is helpful, but inasmuch as the discharge is commonly not more than 30 to 40 gpm, the higher yield formations are not adequately evaluated. For a stated yield of 20 gpm with 120 feet of drawdown, the data are fairly meaningful. However, if a yield of 40 gpm is given with only a few feet of drawdown, then the problem arises that the yield at 100 feet of drawdown might range from, say, 500 to 40 gpm; briefly, all that could be properly said for this example is that the formation looks promising for yields in excess of 100 gpm.

WELL DEPTH AND YIELD

A group of deep wells in hard rock will commonly yield more water than a group of shallower wells in the same formation. The greater number of water-yielding fractures are ordinarily present in the first few hundred feet of hole penetrated, but increments are commonly gained down to a depth of 400 feet or so. Most farm wells and domestic wells range in depth from 50 to 200 feet. They are commonly of limited value in determining the maximum yield of a formation.

Emphasis should therefore be placed on those wells that are 350 feet deep or more, namely industrial and municipal wells for which yield and drawdown data are generally available. Because the number of such wells in a particular study area may be small, it might seem logical to average the yields of all deep wells, domestic as well as municipal and industrial. However, the evaluation of such a mixed lot would be unreliable because all the poor-yield domestic wells in the area would be included (that is, those that were drilled to considerable depth in hopes of obtaining a minimum supply of water). Broadly speaking, only the domestic wells of very poor yield are drilled to more than 200 feet; most domestic-supply wells furnish a small but sufficient volume of water at lesser depths.

Conversely, by selecting only wells 350 feet deep or more, high yields from wells that are finished at less than 350 feet are excluded. If the mixed group of deep wells is weighted with domestic-well failures, a partial correction of the average yield of all deep wells may be made by averaging in the yields of all shallow wells that exceed the average yield of the deep wells. If the shallow wells of higher yield had been continued to a depth greater than 350 feet, they would still yield as much as they do at their present depth (more than the average of the deep wells), and probably more.

In order to obtain a reliable estimate of maximum yield, the data have to be carefully weighed and examined. Two examples of such necessary manipulations follow.

The problem of well depths and yields in Triassic rocks in Rockland County, N.Y. (Perlmutter, 1959), is slightly different. Here wells in the 250- to 350-foot range and the group of wells deeper than

350 feet both yield an average of about 160 gpm. However, there are 14 wells shallower than 350 feet that yield more than 160 gpm. If these wells were deepened to more than 350 feet and included with the deeper group to compensate for the very low yield wells (so-called failures) included in the deeper group, then the average yield of deep wells might be more than 200 gpm. Inasmuch as the Rockland County evaluation deals exclusively with industrial and municipal wells, the adustment should give a figure that is more correct than where domestic wells are included.

Looking at the same problem from a different point of view, the wells in the 250- to 350-foot range already average 160 gpm and, because most of them are presumably developed in highly fractured rock, deepening them by 100 feet or more should bring an increase in yield. An average value reflecting yields where all wells were drilled to 450 feet would then be higher than 160 gpm and probably somewhere between 160 and 200 gpm.

The exclusion of high yields of shallow wells in the evaluation of yields of a group of deep wells can become ridiculous. For example, in the slate, shale, and associated grits and limy beds in Dutchess County, southeastern New York State (Simmons and others, 1961), 17 municipal and commercial wells of intermediate depth (200 to 350 ft) have an average yield of 45 gpm, whereas 10 wells deeper than 350 feet have an average yield of only 25 gpm. Clearly, most wells that yielded poorly were continued beyond a depth of 350 feet in hopes of obtaining more water, and few of these were successful.

In the preceding example the yields of wells of intermediate depth—that is from 200 to 350 feet deep—are desired because the data show that drilling deeper is not warranted. Shaly rocks present a special problem because water-bearing fractures are ordinarily rare below 250 to 300 feet. Therefore, if the deep wells had been discontinued at, say, 250 feet, they might have yielded nearly as much as they do at their actual greater depth. Here, then, the average yield of the intermediate-depth group must be corrected by adding to it the average of the deep wells. In so doing the average becomes less than 38 gpm.

However, in Dutchess County there are a few wells less than 200 feet deep that yield more than 38 gpm. If these are included with the other wells discussed, a final average of about 40 gpm is obtained.

DOMESTIC-WELL RECORDS

In many areas an evaluator may have available only domestic-well records that show nothing more than depths and yields of those wells. Commonly the records would show that many or most of the existing domestic wells are not of optimum depth, and yields given are those obtained at little drawdown.

Although such information is of some value, it should not be relied on if better information on the same types of rocks is available in other areas. As will be discussed later, a reasonable evaluation of a rock formation is believed to be possible only where industrial wells (preferably many) are present. Domestic-well records can hardly do more than suggest how conditions in a particular area resemble or differ from those in geologically similar areas where yields have been established by evaluation of industrial- and municipal-well records.

INDUSTRIAL- AND MUNICIPAL-WELL RECORDS

When a comparison is made between the yields of domestic wells and industrial wells in the same kind of hard rock, the difference is startling. A pumping discharge of 200 gpm is reported from schist in Bronx County, New York City (Perlmutter and Arnow, 1953), 150 gpm from shale in Schenectady County, N.Y. (Simpson, 1952), 300 gpm from metamorphosed sedimentary rocks in Providence, R.I. (Bierschenk, 1959), 1,600 gpm from limestones in western Massachusetts (Petersen and Maevsky, 1962), 600 gpm from Paleozoic sandstones in north-central Pennsylvania (Lohman, 1939), 535 gpm from Triassic sandstones in Connecticut (Cushman and others, 1964), and 365 gpm from gneiss in southeastern New York State (Asselstine and Grossman, 1955). True, these are examples of some of the highest yields known from the various formations mentioned; the average yield of wells in those formations is considerably less. However, the average yield, as estimated from industrial-well records, will invariably be greater, perhaps much greater, than that estimated from a study of domestic-well records, no matter how carefully the domestic-well records are compiled and interpreted.

Data on St. Lawrence County in northern New York State (Trainer and Salvas, 1962) illustrate this difference well enough. Most wells there penetrate Lower Ordovician dolomite, although a few reach underlying Lower Ordovician and Upper Cambrian sandstones. The modest yield of most wells, the specific-capacity data, and geologic descriptions given in the report initially led the writer to the conclusion that although all wells in the area for which critical data are available yield about 50 gpm, an average of about 140 gpm might be obtained from wells drilled to a depth of 200 feet or more and which utilize 100 feet of drawdown. Data on the few deep municipal and industrial wells in the area suggest, however, that this conclusion may be only partially accurate. Two municipal wells almost 300 feet deep are reported to yield 1.8 mgd (million gallons per day), that is, about

600 gpm each. Two other public-supply wells, 316 and 248 feet deep, yield 400 gpm each. An industrial well, depth unknown, yields 400 gpm. Another municipal well, 233 feet deep, yields 60 gpm with 46 feet of drawdown. Therefore, instead of concluding that a little more than the 140 gpm arrived at prevously might be a reasonable estimate of potential yield from deep wells, the limited data from industrial and municipal wells suggest that, with ample allowance for an occasional dry hole, an average yield in the order of 200 gpm well might be obtained from deep wells. Briefly, many domestic- and few municipal-well data indicate that an average of around 50 gpm is available, but, relying on very few municipal-well records, it seems highly likely that yields up to 150 gpm are available. Furthermore, the maximum potential yield of a group of deep wells may be as much as, or even more than, 200 gpm.

The desirability of relying on municipal- and industrial-well records to the fullest extent possible cannot be overemphasized. Such wells represent efforts to develop a maximum supply of water, and consequently the conclusions based on the performance of such wells will be of a high order of reliability.

Taking another example, the average yield of all wells in the Triassic sandstones of north-central Connecticut (Cushman, 1964, p. 33) is 27 gpm, but the average yield of 64 industrial wells is 169 gpm. The industrial wells are drilled much deeper than the average well and are pumped to produce a maximum supply of water. Adjusted where possible to 100 feet of drawdown, the yield might be about 155 gpm. A yield of either 169 gpm as given by Cushman or 155 gpm as given by the writer for wells in Triassic sandstone might seem very high, but an average of 65 wells in the same type of formation in Rockland County in southeastern New York (Perlmutter, 1959) was found to be even higher, 192 gpm. (In the Rockland County group, one well that yields 1,515 gpm with 60 feet of drawdown was omitted from this study because that yield is significantly higher than that of all the other higher yield wells and may reflect unusual conditions.)

Similarly, records of industrial and municipal wells in gneiss and schist in Westchester County in southeastern New York (Asselstine and Grossman, 1955) give a better picture of the potentialities of those formations than can be obtained from records of wells in rural New England. Forty-seven wells in schist in Westchester County yield an average of 65 gpm, according to the writer's method of evaluation. (One well that pumps 400 gpm is excluded from the group averaged.) Considering that almost no poorly located wells were eliminated from the group, the average yield of wells in schist might be as much as 80 or 90 gpm if better well sites were chosen.

Twenty-nine industrial and municipal wells drilled in gneiss in Westchester County have an average yield of about 35 gpm. (One well that yields 365 gpm with 60 feet of drawdown is excluded.) However, about half the wells on which the average is based are less than 300 feet deep. Furthermore, many of the wells supply dairies and other consumers whose needs are only moderate. Hence, the average yield of 35 gpm probably represents the average need in the area rather than the maximum potentials of the wells. A yield somewhat higher than 35 gpm should be assigned to wells in this type of rock on the basis of the data used.

Selecting only industrial wells of any depth for the averaging will not give a foolproof answer. Where many of these are shallow wells of somewhat modest yield, correction of known yields to probable yields at a depth of 400 feet is not really feasible. Furthermore, the wells are hardly ever evenly distributed throughout the area, and the question may be asked, "What proportion of the well used in the assessment is located on favorable sites and what proportion is in locations that are obviously unfavorable?" As noted above, the majority of wells are probably not located in the most favorable sites.

SOURCE OF RECHARGE

In studying records of wells over a wide area, some marked differences in yields from one type of rock are seen in different regions. Some of these differences may reflect the insufficiency of critical data in some of the areas considered, and others are due to geological differences between the areas compared. However, even within relatively small areas, great differences in yield occur that are difficult to explain by differences in bedrock geology. In many areas these anomalies can be explained by differences in available recharge.

The character of the rocks will obviously limit the amount of water that can be induced to flow to a well. However, where a source of ready recharge is available—a nearby stream or thick saturated overburden—commonly more water can be induced to flow to the pumping well than if the well were drawing only upon storage within the fissures and joints in the rock mass and occasional recharge from rainfall.

A spectacular and obvious example of such differences due to the influence of a nearby source of recharge is seen in the lowermost Mississippian sandstones in Pennsylvania. A few records in the south-central part of the State (Lohman, 1938) and in western Maryland suggest that 100 gpm might be the maximum that could be expected of wells in that formation. However, in north-central Pennsylvania, Lohman (1939) lists a number of wells whose average yield is 150 gpm. Excepted from this averaging is a group of 15 wells, which have an average discharge of 460 gpm with 15 to 60 feet of drawdown. The explanation for these high yields becomes aparent from a sketch map that shows these wells to be located along a small river. The wells are constructed with casing that extends through alluvium into bedrock. Here the river keeps the alluvial cover saturated at all times, and the saturated alluvium, therefore, provides an unfailing source of recharge for the wells drawing water from the underlying sandstone.

The 300-gpm yield of two wells in granitic rocks in the Richmond area, Virginia (Sanford, 1913), can be explained in part by the very high drawdown. In one of these wells the pump is set 350 feet below the surface, so that at least 270 feet of drawdown is available. However, these high yields may also be due to the fact that in this area bedrock is overlain by saturated Coastal Plain sediments that provide an adequate source of recharge to the underlying bedrock. Seven other old industrial wells there are reported to yield from 100 to 200 gpm although two of these are only 248 feet deep.

In Union County, in eastern New Jersey, the average yield of a group of 117 wells in Triassic rocks is on the order of 300 gpm (Nemickas, 1970). The highest yield obtained from any one well is 870 gpm with 73 feet of drawdown. In Rockland County, N.Y., the yield of one well is reported to be 1,515 gpm. The higher-than-average yields, and the exceptionally high yields of individual wells in Triassic rocks in both northern New Jersey and southeastern New York are ascribed to the presence of saturated glacial sediments overlying the bedrock in which the wells are finished.

Hall (1934) notes that in southeastern Pennsylvania some very high yields are obtained from shales lying beneath a saturated gravel cover.

In Rhode Island the importance of stratified glacial formations that function as a source of recharge is well recognized. Bierschenk (1954) states that in the Bristol quadrangle yields of wells in bedrock vary according to the type of glacial sedimentary cover. Although valley locations, commonly marking zones of fissuring, are considered optimum sites for hard-rock wells, Bierschenk points out that 58 wells located in valleys in the Bristol area have an average yield of 34 gpm, whereas 200 wells located on plains have an average yield of 45 gpm. The valley wells, on the average, are a little deeper than the plains wells. The difference may be due to the more common presence of till overburden in the valleys than on the plains.

High yields are also reported (Bierschenk, 1959) from rock wells in the Providence, R.I., quadrangle. Here are many industrial wells in a humid environment where recharge from stratified drift and large

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streams is commonly available. One well yields 500 gpm, four yield around 300 gpm, five yield 200 gpm or more, and 14 yield 100 gpm or more. In Virginia and Maryland roughly comparable yields have been obtained from somewhat similar rocks of Precambrian age. There the saprolite, the thick residual decayed rock cover, must be functioning with a reasonably high degree of efficiency as a source of recharge. In New England, glacial action has scraped off the old weathered rock cover, and consequently most rock wells in New England have somewhat lower average yields than in the unglaciated States.

In coastal Massachusetts (Maevsky and Drake, 1963) there are many high-yield wells developed in crystalline and metamorphic rocks (one yields 500 gpm; one, 250 gpm; one, 200 gpm; and 10, 100 to 170 gpm). Almost all these high-yield wells are located near major streams from which water either percolates laterally to sediments lying above bedrock or directly downward to bedrock fissures beneath the streambed. In metamorphic rocks in the Bangor area, Maine (Prescott, 1964), the few high-yield wells (75, 90, and 100 gpm) are near major streams, whereas "inland" wells yield 50 gpm or less. Recharge from the river is shown by the fact that two heavily pumped wells along an estuary eventually yielded brackish water. Two shallow wells in metamorphic rocks on an island are reported to have the spectacular yield of 350 gpm. Presumably heavy discharge can be sustained briefly because there is a nearby limitless source of recharge from the sea. Pumping fresh water from storage for brief periods is possible in that sea water displaces fresh water only at the outer edge of the cone of depression and in nonpumping periods local recharge tends to drive the sea water outward again.

Till has a high porosity and may be an important source of recharge where small yields are concerned. Crain (1966) states that in the Jamestown area of southwestern New York, domestic wells are better producers where the shaly rocks are overlain by at least 15 to 20 feet of till. However, as pointed out by Grossman (1957), in Putnam County, N.Y., the yields of rock wells where bedrock is overlain by sand and gravel are generally twice as great as where it is overlain by till, which, although highly porous, is poorly permeable.

The source of recharge to wells in carbonate rocks (limestones and dolomites) may be particularly hard to evaluate. The availability of recharge will, of course, be a dominant factor in the long-term performance of a high-yield well in carbonate rocks. Solution channels below the water table may extend for miles in limestone, and deciding that flow to the well from distant storage and sources of recharge can or cannot occur may simply not be possible unless a lengthy pumping test is conducted.

In western Massachusetts, yields of 17 of the deeper industrial wells in carbonate rocks (Petersen and Maevsky, 1962) range from 100 to 1,600 gpm. If two wells yielding 1,400 and 1,600 gpm, respectively, are omitted from the averaging, the average yield is 250 gpm. The question remains, however, as to how meaningful a conservative figure of 250 gpm might be here in view of the real possibility that a single well susceptible to recharge from a nearby river might yield over 1,000 gpm.

Evaluation of the problem is further complicated by data from the Friedensville mine in Pennsylvania (Wood and others, 1970); as much as 30,000 gallons a *minute* has been pumped from a deep shaft. Recharge water flows to the mine shaft from an area of more than 42 square miles. Recharge from a fairly wide area must also be flowing to five closely spaced wells at Elkton, Va., that yield a total of 8.5 mgd, although capture of flow from nearby small streams may also be a factor.

WELL CONSTRUCTION

As was stated in the previous discussion of average well yields, for some estimates yields of one or two exceptionally high-yield wells were omitted from the group selected. Those yields excluded represent special circumstances, such as locations along a fault zone. A few other wells have been omitted from place to place because they seemed uncharacteristic of the area.

The writer believes that the high yield of at least one well penetrating crystalline rock is due to direct leakage from overlying stratified sand. Such leakage may result from poor seating of the casing, from damaged casing, or retraction of the casing slightly from its bedrock seat by the driller. There is, of course, no way of telling to what extent recorded well yields in any area may have been augmented through leakage from above in the immediate vicinity of the hole, but the elimination of a few unusually high well yields here and there tends to minimize any such possible effect.

On the other hand, there is the very real possibility that where casing extends 50 or more feet into bedrock, yields will be smaller than where casing is seated within 5 or 10 feet of the upper surface of that rock. In most places the uppermost few tens of feet of rock penetrated is the most fissured. Drillers who are anxious to obtain a sediment-free rockwell without subsequent pumping and surging may have, in many places, driven casing much deeper into the rock than is necessary and in so doing have shut off much of the available inflow. Hence, apparent yields in some areas may be lower than what is truly characteristic of the rock type.

Just what is a rock well (and what should it be) in an area where weathered rock extends 50 to 100 feet below the level of saturation and merges almost imperceptibly with solid rock beneath? Here most drillers will almost certainly shut out some water-bearing material when driving casing down to a firm footing. But if the lower 10, 20, or 30 feet of casing is perforated and the annular space between the casing and the walls is sand packed or gravel packed (and subsequently developed) to take advantage of the material that is transitional between thoroughly weathered residual material and firm hard rock, is this a rock well or is it a well in unconsolidated material? The question is academic, but the subject is brought up to suggest that somewhat higher yields than are discussed later might be available from rock wells if they were constructed to take full advantage of the water-bearing capacity of any weathered rock material which overlies the firm unmodified bedrock.

There may be difficulties in clearing a well that admits water from the zone above firm rock, just as there is difficulty in clearing some wells finished in granular sediments. Nonetheless, the writer feels that, in constructing wells in many hard-rock areas, more thought might be given to development of the soft rock and more thoroughly weathered rock (saprolite) in the upper part of the drill hole.

EVALUATION OF A WELL-DOCUMENTED AREA

A report on the ground-water resources of Montgomery and Berks Counties in eastern Pennsylvania (Longwill and Wood, 1965) is particularly suited to show the problems in evaluating yields of wells in a hard-rock area. There are a great many industrial and municipal wells in the area, the data are more complete than those in most reports, and a map in the report shows not only well locations but also drainage and topography. Here the data can be evaluated much more closely than is possible in most areas.

Industrial wells in a cluster along the Schuylkill River in Triassic sandstones yield 120, 147, 200, 255, 75, and 430 gpm. A simple average yield of these wells is 204 gpm.

The source of recharge for all wells in a nearby river, but the well with the highest yield is closer to the river than the other five and the poorest well is the most distant. That poorest well is a little deeper than the highest yield well in the group. With respect to the four wells equidistant from the river, the deeper wells yield more water than the shallower.

Downriver at a State school, seven wells in the same formation have an average yield of 114 gpm. Drawdown data are available for five of these. All wells are on high ground, and no obvious linear surface feature can be discerned that might account for marked differences in yield. One of the two highest yield wells is fairly near the river, but the other is more distant from the river than the lowest yield wells. Here we find that a more detailed study simply emphasizes the difficulty of making generalizations about the occurrence of ground water in hard rocks.

Elsewhere in the area a municipality has drilled 15 wells whose average yield is about 95 gpm. However, the map shows that four conspicuous failures were drilled in the same place, presumably at the town's water tank. When three of these are eliminated (in any reasonable development only one failure will be drilled in one place), the average is 114 gpm. If three of the yields for which drawdown is given in the remaining group of 12 wells are adjusted, the yield is reduced to 105 gpm. Two low-yield wells are less than 300 feet deep, and, if these may be eliminated, the yield arrived at for the 10 remaining deep wells will be 118 gpm. This is about as far as the data can be refined. Unfortunately, drawdown data are not available for seven of the 10 wells in the group. Inasmuch as two of these pump 200 and 240 gpm, probably more than 100 feet of drawdown is utilized, as is true in three of the higher yield wells for which drawdown was given. A final estimate of average yield might be about 110 gpm.

There are 17 other deep industrial wells in the same area that have an average yield of 170 gpm after adjustment to 100 feet of drawdown. The adjustment is very slightly downward from the actual average pump discharge. Adding these to the selected group of 10 wells discussed in the preceding paragraph, average yield becomes about 150 gpm rather than 110 gpm.

Although the 150 gpm seems reasonable because this yield falls about midway between the spread of other averages determined previously (204 to 114), there is still another group of five closely spaced deep industrial wells nearby that might be included. These yield an average of 12 gpm. Adding these to the group already considered, the overall average would be only 130 gpm. However, this is a cluster and should be considered to mark only one site. If these five wells are considered as one well (as they should be considered, inasmuch as they represent a single site), the 150 gpm average declines only to about 145 gpm. (Five high-yield wells in a cluster would also be considered as one well in an averaging of well yields.)

Apparently many of the better wells are drilled in or near small headwater streams. For example, a couple of rather good producers are in the shaly Lockatong Formation, a generally poor aquifer. Conversely, the four closely spaced old municipal wells in the center of town, all of which were failures, and a group of five very poor industrial wells in the Brunswick Formation, generally a good aquifer, are all located on a drainage divide.

Thus, if failures in two drainage-divide areas had been recognized as showing that drilling there was fruitless and if further multiple-well drilling had been carried out in generally lower areas more susceptible to recharge, the average yield of all wells would have been about 145 gpm instead of 120 gpm, the average of all existing industrial and municipal wells in the area. It would not have been necessary to understand the suggested reason for differences in yield in order to obtain the 150-gpm average. Simply accepting the fact that two areas proved unprofitable when drilled initially would have been sufficient, assuming, of course, that widely scattered drilling sites would be available.

So far, average yields are 204, 114, and 145 gpm. The highest average yield is from a group of wells near a major stream, and one well in that group has an especially high yield due to rapid and easy recharge from that source.

A fourth cluster of wells at the State penitentiary is on high ground within a more or less dendritic pattern of small streams that join a larger stream 1 mile west of the institution. The site appears to be moderately favorable. The average yield of seven wells as given in the report by Longwill and Wood (1965) is 178 gpm. The drawdown in a well yielding 355 gpm is 87 feet; and, what is more interesting, three wells with an average yield of 116 gpm utilize only 11.5 feet of drawdown, and a well yielding 300 gpm utilizes only 18 feet of drawdown. The expected average yield would be higher, with 100 feet of drawdown, than the 178-gpm average already noted. However, increasing the drawdown beyond 11 or 12 feet may have resulted in so little increase in yield that the installation of a larger pump and longer pump column was not worthwhile.

The source of recharge for this group of wells is undoubtedly in part the nearby small streams, but in largest part it may be the large stream 1 mile distant. Pumping levels (water level plus drawdown) range from 8 to 72 feet above sea level, whereas the altitude of the stream 1 mile distant is about 135 feet above sea level.

The manner in which the data pertaining to this last group of wells should be used in an overall evaluation is most questionable. To begin with, the seven wells in no sense represent more than one point in the ground-water province, and only one notation should be used in averaging the yields, arithmetically or otherwise.

The averages obtained thus far are 204, 114, 145, and 178 (or more) gpm. One could say at this point that the average yield of properly located multiple deep wells in the area should be about 160 to 165 gpm.

However, only in the third group, averaging 150 gpm, are the wells scattered widely, and probably this group more nearly approximates the representative average yield.

As a final step, the yields of all deep industrial and municipal wells in the area were arithmetically averaged. The list included 73 wells for which drawdown is not listed and 38 with drawdown known. These 111 wells average 138 gpm. Fifteen wells that are less than 350 feet deep but which have high yields are included in the averaging. Presumably these would yield somewhat more water if they were continued to a depth of 500 feet, and perhaps an overall average of about 150 gpm would then be considered reasonable.

Although results of differing approaches to estimates of average yield may tend to converge, as happened in the study just outlined, care must be taken to try to exclude the occasional well whose yield lies completely outside the range of almost all the other wells. Such wells may represent special conditions. In an area of Triassic sedimentary rocks discussed earlier, a low-yield industrial well that penetrates a basalt flow a short distance below the surface should be discounted. A well begun in high-yield carbonate rocks might penetrate low-yield shales at shallow depth, and so on. In the Montgomery and Berks County area, the yield of only one well stands out away above the group in which the maximum yield is about 400 gpm. That exceptional well is reported to yield 750 gpm. Generally such a report should be regarded with suspicion, as being based on a very short pumping test, optimism on the part of the owner, or some other factor. In this particular case, the well has been drilled along the fault line between the Triassic and older formations, and the report is believable. However, although drilled in Triassic sandstone, that well should not be included with the many others in the area because it represents an easily distinguished special location and should be reported separately. In other situations clear-cut distinctions between especially favorable and average ground cannot be drawn. As discussed earlier, eliminating one or even two particular high yields from an otherwise clustered group of yields should do much to relate the final estimates to ordinary conditions.

As an example, where yields of all but one of a group of wells range from 30 to 250 gpm, a well yielding 400 gpm is considered abnormal, and its yield is not likely to be matched by any one of five wells drilled in some future development. Rather, five wells drilled at chance locations will tend to yield somewhere around the average (140 gpm) of the remainder of the group of industrial and municipal wells, although there is a reasonable chance that one of the five wells might yield nearly 250 gpm.

Following this line of reasoning to its ultimate conclusion, clearly in any area under study a valid average yield for a group of wells will be obtained only by chance unless wells for which data are available are spaced to encompass average conditions throughout the area of study. Furthermore, where only five wells are subsequently drilled in that area, even though they are widely separated, they will not likely obtain the true average yield except by chance. They may be located in somewhat more favorable or somewhat less favorable ground than that represented by average conditions and may yield more or less than the true average yield. However, where located on the basis of hydrologic advice and with a reasonable distance between sites, the yields of five wells will likely average to approximately what had been determined for wells separated and not clustered in one area. By increasing skill in recognizing favorable well sites and assuming that the hydrologist has both time to study the ground and option to select what he considers the most favorable locations, yields of a group of wells selected on the basis of sound hydrologic principles may average higher than those determined from existing wells.

It might be suggested that the median yield, rather than the average yield, would more properly represent the results obtained from drilling five wells. In other words, the yields would be more on the order of what most wells yield rather than the average of all wells. A median yield might better represent what might be obtained from one well in a particular type of hard rock. However, when five wells are drilled, a fair spread of geologic and hydrologic conditions will be met, and the yields of that many wells should tend to the average rather than to the median.

ESTIMATED AVERAGE YIELDS OF WELLS IN CONSOLIDATED ROCKS

The data from which the average yields of wells in hard-rock formations are estimated are summarized on plate 1. Considerable variation in apparent average yields may be noted. Many of the apparent differences are a function of the degree of effort on the part of water developers to obtain a maximum volume of water from wells. For example, significant yields from wells in crystalline rocks (granite and schist) can be demonstrated only in those areas where industrial and municipal supplies were needed—as in Richmond, Va., the Washington-Baltimore area, and coastal New England. Although individual wells in carbonate rocks (limestone and dolomite) are known to yield very large quantities of water almost everywhere, a high average yield for wells in these formations can be shown only where a group of a dozen or more industrial wells is the basis for evaluation, as in western Massachusetts. Industrialized eastern Pennsylvania and southeastern New York State yield critical data on wells obtaining water from shaly beds. Records of domestic wells in the Triassic sandstones fail to suggest that fairly high yields may be obtained from those rocks, but where many industrial wells have been drilled, the sandstone is commonly a rather abundant producer.

Where few or relatively few industrial wells are present, apparent average yields are lower than where a larger number of industrial wells are available for study. Some average yields may be less than their true values owing to a relative preponderance of wells that supply schools, restaurants, hotels, and other nonindustrial establishments. Many such consumers do not attempt to develop a maximum yield from their wells, their needs being met when 15 to 30 gpm becomes available.

Some estimates are based on yields of wells of less than optimum depth. In most formations these wells will not produce as much as wells 400 to 500 feet deep. The difference in apparent yields between shallow and deep wells is illustrated in estimates of yields in granite. Average yields are fairly high in Virginia (Richmond area), where most of the wells considered are deep, but in southeastern New York State the 20- and 40-gpm average yields of commercial wells (hotels, rather than industrial plants) in Putnam and Dutchess Counties reflect the fact that most of the wells are relatively shallow. Here much more reliance should be placed on the yields obtained from the Virginia group of wells. The apparent low yield (less than 50 gpm) of wells in Upper Devonian shales in Dutchess County, as compared with 150 gpm and 90(?) gpm in adjacent Delaware and Greene Counties in southeastern New York, may likewise reflect the lack of industrial wells in Delaware and Greene Counties.

WATER-BEARING FORMATIONS

The water-bearing formations on plate 1 are arranged in order of age, the older formations being at the bottom of the chart and the younger at the top. However, the group of Precambrian formations are not in chronological order, and, furthermore, any one designated rock type may include more than one formation; that is, granite in Virginia may include two different granites, neither of which is necessarily exactly equivalent in age to a granite in Pennsylvania or New England. Many New England granites are late Paleozoic in age.

The massive Cambrian to Ordovician limestone aquifer that extends from Virginia to southern New York (in the North Atlantic region) may not be the exact age equivalent of the limestones of the Taconic sequence in easternmost New York and western Massachusetts. The exact age of the clastic sediments below the limestones of the Taconic sequence is also doubtful. Correlation of metamorphosed Paleozoic sediments in New England with specific formations in the Appalachian area is not implied.

PRECAMBRIAN ROCKS

MARBLE

The ancient carbonate rocks of the Piedmont province have a very limited distribution. A few wells in and around Baltimore and in New York City have developed high yields in these rocks, but data are so limited that an average yield of about 100 gpm is all that can be assigned at this time.

GREENSTONE

Greenstone is another Precambrian formation that has a rather limited distribution. The formation is generally considered a poor aquifer but, on the other hand, few attempts have been made to develop greenstone as a source of water for industrial use. Therefore, its potential cannot be properly evaluated at this time. In Allegany and Washington Counties, Md. (Slaughter, 1962), where more than minimum effort was made to develop water from greenstone, an average of 50 gpm was obtained from nine wells. Three wells in Frederick County, Md. (Meyer, 1958), yield an average of over 80 gpm with low to moderate drawdown. However, three deep wells in Fairfax County, Va. (Johnston, 1962), yield an average of only about 25 gpm. Drawdown is not known. The formation should be regarded as unreliable as a source of more than minimum supplies of water until more is known of its characteristics.

The Catoctin Formation in Virginia, although commonly referred to as greenstone, is made up of several kinds of rock, among them arkose and conglomerate. A well at Warrenton, Va., that yields 550 gpm with 48 feet of drawdown is developed in an arkosic phase of the Catoctin Formation.

SCHIST

Schist of various origins is somewhat widely distributed in the belt of Precambrian rocks east of the Appalachians and in New England. Some schists are plastic, and water-transmitting fissures in them tend to close. However, many of the schists have been injected by or have absorbed granitic fluids, are quite brittle, and tend to retain open fractures created during earth movements. Hence, some or all schists in this area are fairly good water-bearing formations. As seen on plate 1, average yields of about 100 gpm have been obtained from industrial- and public-supply wells developed in schist in the greater Washington area, and 80 gpm has been obtained in the Philadelphia area. Any one well in schist may yield only 5 or 10 gpm, and the average yield given above will be obtained only in a multiple-well development.

Higher yields will be more likely be obtained from wells in schist where wells are located along fracture traces. Well development in the Shetucket River basin of eastern Connecticut (Thomas and others, 1967) is not sufficient to characterize maximum potential yields of either the schists or the gneisses that make up bedrock in that area, but study of the data does show conclusively that nearly all hilltop wells are very poor producers and that the larger yields are obtained only on the lower flanks of the mountains and in valleys on or near zones of fracture and easy recharge.

The records from Westchester County in southeastern New York illustrate the difficulty of arriving at a representative yield for multiple wells in the schist. Sixteen wells ranging from 250 to 350 feet in depth yield an average of 86 gpm. Correction for drawdown would raise this figure slightly. However, 30 deeper wells, 350 to 830 feet in depth, yield an average of only 50 gpm (omitting one well of very high yield that is not characteristic of the group). Apparently here most of the wells here that were drilled beyond 350 feet were the poor producers, whereas the abundant producers were drilled only to an intermediate depth. Combining the yields of all shallower wells with the deep wells results in a figure of about 58 gpm. If the wells of intermediate depth and better yield were drilled deeper, they would undoubtedly yield somewhat more water. Hence, choosing a yield of 65 gpm, as shown on plate 1, seems conservative.

GRANITE GNEISS

Granite gneiss (banded granite) seems to be a poor water-bearing formation. Records bearing on an intensive development of wells in gneiss are available only from Westchester County in southeastern New York State. There about half the wells chosen for averaging are less than 300 feet deep. Furthermore, two public-supply wells of moderate depth yielding 365 and 250 gpm were omitted. If these two wells represent results that may be obtained from place to place, the overall average yield is about 50 gpm rather than the 35 gpm given on the chart. In Putnam County, N.Y., deep wells penetrating the gneiss are rare, and the highest yield reported is 48 gpm at a depth of 135 feet. The data are not considered diagnostic of maximum yields available from the gneiss.

By selecting well locations in valleys, many of which contain fracture zones ordinarily subject to good recharge from overlying sands, average yields greater than 50 gpm can probably be obtained from granite gneiss in glaciated terrane.

GRANITE

Although granite is ordinarily considered to be a rather poor water-bearing formation because many wells ending in granite have low yields, high yields occasionally have been obtained where the wells are 400 to 450 feet deep and where a fairly large drawdown is used. The assemblage of 44 well records in the Richmond-Petersburg area, Virginia, from which an average yield of 90 gpm was obtained, includes five deep wells that are definite failures, each yielding only a very few gallons a minute, and 11 wells that are less than 250 feet deep. Records elsewhere are too few or the wells are too shallow to characterize the yields in granite except in southeastern Massachusetts (Petersen, 1962), where yields comparable to those at Richmond were determined. In both localities a ready source of recharge is available; in the Richmond-Petersburg area bedrock is overlapped by Coastal Plain sediments, and in southeastern Massachusetts most wells are located on low ground covered with sediments of glacial origin.

SEDIMENTARY ROCKS

LOWER CAMBRIAN

The potential of the more or less metamorphosed Lower Cambrian sedimentary rocks—sandstone, shale, slate, and quartzite—cannot be estimated from available data. Scattered records from wells in Virginia, Maryland, and south-central and southeastern Pennsylvania suggest that the sandstone and quartzite may be fairly good water-bearing formations and that the average yield of multiple wells may range from 50 to 100 gpm. The shales are almost certainly poor yielders, but slaty shales and slates may be fairly productive, as discussed under the heading "Ordovician Shale and Minor Sandstone."

CAMBRIAN AND ORDOVICIAN CARBONATES AND SHALE

Only a few data are available on the yields of wells developed in the Lower Cambrian dolomite that is present from Virginia to Pennsylvania, but what data are available strongly suggest that large yields can be obtained from properly located well in this formation. Wells located in fracture traces of Paleozoic carbonate rocks will likely have large to very large yields, whereas those drilled in unfractured massive rock will generally have very poor yields.

From 1,500 to 2,000 feet of limy shales separates the Lower Cambrian dolomites from a great thickness of Upper Cambrian and Ordovician carbonate rocks in Virginia and southeastern Pennsylvania. Little is known of the water-bearing characteristics of the shale, but it is presumed to be a very poor aquifer. On the northern rim of the Adirondack Mountains in New York State, a thick sandstone is present beneath thick Cambrian and Ordovician limestones. Little is known of its potential as a water producer. Older Cambrian rocks are not exposed in the northern part of the area except for the Taconic sequence in easternmost New York and westernmost New England.

The thick limestones of Late Cambrian and Ordovician age are the best water producers in the area. As an example, one well in Virginia yields 1,200 gpm with only 10 feet of drawdown. The maximum yield of that particular well might be several times the stated 1,200 gpm. A well in Washington County in eastern New York State yields 2,000 gpm; the drawdown is not known. The average yields of wells in these limestones, many of which may be so located that they do not penetrate large solution channels, is about 300 gpm.

Wells in thick limestones located on the basis of careful geological study should have much higher average yields, perhaps about 700 gpm (1 mgd). Techniques for recognizing fracture zones in limestones have been advanced markedly in the last several years, but the apparent value of the new methodology in many different limestone terranes is yet to be demonstrated.

Along the border of New York and New England, a series of Cambrian and Ordovician rocks has been thrust against the more stable area to the west. These rocks make up what is known as the Taconic sequence. Within this group are thick limestones that are more or less age equivalents of the Cambrian and Ordovician limestones previously discussed. Structural deformation has caused great shattering of the rocks from place to place. Some wells with very high yields have been developed in this shattered area. In western Massachusetts 17 industrial wells have an average yield of 250 gpm, excluding two wells that yield 1,400 and 1,600 gpm. (The two wells of highest yield are excluded because they may represent especially favorable conditions near a major fault.)

Seventeen wells in this limstone in Dutchess County, N.Y., have a much lower average yield. The rock there may be much less shattered than in western Massachusetts. However, only six of the 17 commercial and small-municipality wells used in the averaging are deeper than 228 feet, and seemingly there has not been a general effort made to develop a maximum supply of water here.

The very high yields obtained in several localities suggest that more than 250 or 300 gpm per well may be available in many places from limestone. Recent studies in Pennsylvania (Wood and others, 1970) tend to show, however, that past estimates of the yields of wells in Appalachian limestones may have been very conservative.

In Lehigh County, Pa., there are 30 wells in Cambrian and Ordovician carbonate rocks that yield from 500 to 1,800 gpm each. The 1,800-gpm-well is only 130 feet deep. The three deepest wells are around 800 feet deep and yield from 500 to 540 gpm each.

In the little Saucon River valley, also in Lehigh County, Pa., the Friedensville mine was pumped at a rate of 30,000 gpm from the 400-foot level for many months. A discharge of 13,000 gpm has been seen to issue from a hole 3 feet in diameter in the shaft well, and 8,000 gpm from "several small openings" (Wood and others, 1970). A cone of depression has extended throughout the entire surrounding limestone area, as shown in a map accompanying the report. A discharge of as much as 21,000 gpm has been sustained for several years. (About 4,000 gpm of the discharge was recirculated water.)

In the writer's opinion the enormously high-yield "well" at the Friedensville mine probably does not represent a unique hydrologic situation. At Elkton, Va., five wells located 15 feet apart yield a total of 8.5 mgd or about 6,000 gpm. The question arises as to what might be the available ground water there if a large-diameter shaft were driven to 400 or 500 feet and a 400-foot drawdown were utilized.

In much of the Appalachian Valley, where structural deformation has been severe, yields of 1,000 gpm or more should be generally available if conventional wells are situated along intersections of fracture traces. Favorable sites are not restricted to the foot of the Blue Ridge. High-yield wells are known in the central and west-central part of the Valley of Virginia at Blacksburg, Montgomery County, Va., at Pearisburg, Giles County, Va., and at Athens and Princeton, Mercer County, W. Va. It is also interesting to speculate on what might be done with large-diameter shafts and oversized pumps in these areas.

Various shales, slates, grits, and quartzites are associated with limestones of the Taconic sequence. Data from New York localities suggest that average yields in these formations are poor. The one industrial well that ends in quartzite in western Massachusetts does have a high yield, 485 gpm with 31 feet of drawdown, but high yields of this type may not be characteristic of other structurally less disturbed areas.

ORDOVICIAN SHALE AND MINOR SANDSTONE

A clay shale would be expected to yield relatively small quantities of water to wells and in beds of that type the average optimum yields of wells may be on the order of 25 to 50 gpm. However, in the Appalachian area of folded rocks, some shales have become slaty and, being more brittle, are more fractured and, hence, are better water producers. Elsewhere, shales commonly include limy or sandy lenses which again render them better aquifers than clay shales.

Wells in the somewhat slaty shales of southeastern Pennsylvania are moderate producers. Thirty-three wells in that area, nearly all of which are deeper than 350 feet, have an average yield of 90 gpm. The two shallow wells included in this average yield 208 and 120 gpm. Nine of the deep wells in the group yield from 150 to 250 gpm, and seven of the deep wells yield 20 gpm or less. The shales are sandy in Maryland and limy in Virginia. Presumably, they may yield about as much in those areas as they do in southeastern Pennsylvania. Data are very meager, however, and more cannot be said of their potential at this time.

Data are also few on industrial and municipal wells ending in the Ordovician rocks in New York State. Most of the shales of this age seem to be poor producers, although just southeast of the Adirondacks the shales are somewhat sandy and should be fairly productive. In Schenectady County the only two industrial wells listed in one report each yield 150 gpm at a depth of about 200 feet. In Dutchess County most wells tap slaty shales of the Taconic sequence. The average yield of 18 deep industrial and municipal wells there is about 50 gpm.

Wells in clay shales clearly obtain most of the water available within 200 feet of the surface, but limy shales and sandy shales may yield desirable increments of water from much greater depths.

SILURIAN SHALES AND SANDSTONE

By far the greater part of the Lower and Middle Silurian section consists of shale, limy shale, and sandy shale. The limy and sandy members that are present in Pennsylvania and Maryland are moderately productive. In northeastern Pennsylvania average yield of deep wells in somewhat sandy shale may be as much as 75 gpm. Comparable or possibly even greater yields may be obtained from wells southward into Virginia.

In New York the shales are somewhat slaty. Records of a few domestic wells in Seneca County and several industrial wells in Wayne County suggest that yields may also be about 75 gpm in that area. However, in New York State the Silurian shales yield brackish water from place to place, even from rather shallow wells. Somewhat undesirable "black sulfur water" is obtained from Silurian shales in northern New York State. This water contains black suspended matter, presumably iron sulfide, and has an offensive odor.

The basal Silurian sandstone (as well as minor sandstones in the Ordovician) is relatively thin and stands out as prominent ridges above a low shaly terrane. Hence, few wells are developed in it, and nothing definite can be said about its water-producing capabilities. In areas of strong folding the sandstones are quartzitic and should be greatly fractured. Although possibly highly permeable in places, sources of easy recharge may be lacking and, therefore, even if high yields were obtained from wells drilled in it, those yields will probably be difficult to sustain. Furthermore, water levels vary greatly in the ridge-making formations. During the periods of heavier rainfall, water levels may be high and yields of wells may be copious, but during drier intervals water levels decline sharply and yields may greatly diminish.

UPPER SILURIAN AND MIDDLE DEVONIAN LIMESTONES

The limestones in this unit may be prolific as the Cambrian and Ordovician carbonates, but their exposures are limited and few industrial wells have been drilled in them. Yields as much as 500 gpm have been reported from individual wells in Lower Devonian limestones in south-central Pennsylvania and eastern Maryland, but the Middle Devonian limestone which appears to be an excellent aquifer in New York State grades southward to limy shale in Pennsylvania where it is clearly a less productive formation. Data on wells in the Upper Silurian limestone are meager but do suggest that the formation may be highly productive.

In the Appalachian area a thin but prominent sandstone bed separates the Middle Devonian shaly limestone from the underlying Lower Devonian to Upper Silurian limestone. In Pennsylvania and eastern Maryland excellent yields have been developed from a few wells in this sandstone formation; one well in Pennsylvania yields 400 gpm with 50 feet of drawdown and another 250 gpm with 60 feet of drawdown. Both wells are less than 250 feet deep. The formation may best be thought of as offering some interesting possibilities where a source of recharge seems likely.

The Silurian limestones present in a small area in northeastern Maine (G. C. Prescott, Jr., written commun., 1969) may be as good aquifers as some limestones in the Appalachian area. The average discharge of 28 wells, presumed to be industrial wells, is 130 gpm. Adjusted for drawdown, the average yield is 150 gpm. However, in this average four wells are omitted because they have very little drawdown and adjustments of their yield to 100 feet of drawdown might be much too high or much too low. Two of them yield 40 gpm with 2 feet of drawdown, one yields 150 gpm with 7 feet of drawdown, and one yields 100 gpm with only 1 foot of drawdown. The highest yield from a well in these limestones in Maine is 355 gpm with 40 feet of drawdown. This well is considered to yield 460 gpm at 100 feet of drawdown. The poorest well yields 4 gpm at a depth of 768 feet with 180 feet of drawdown. The conclusion reached is that multiple wells in this aquifer should average more than 150 gpm.

DEVONIAN SHALES AND SANDSTONES

The Middle and Upper Devonian shales show the influence of an ancient rising landmass east of New York State. The rocks in New York and southward into Pennsylvania vary in their makeup relative to the distance from that landmass. Near the landmass rocks are sandy, but at some distance the formation becomes a clay shale. These beds make up what is known as the Catskill delta. In eastern New York and in eastern parts of Pennsylvania, thick sandstone beds may predominate, but more to the west and south, the formations are essentially sandy shales and shales.

Few data are available on the lower shales in the Devonian sequence. A few records of wells in somewhat sandy shales in Pennsylvania show that moderately high yields are available from place to place. Records are too meager to permit any overall characterization of the formations in New York State, but southward into Maryland and Virginia the Middle Devonian shales are seemingly poor aquifers.

Some unexpectedly high yields have been obtained in Pennsylvania and southeastern New York State from Upper Devonian beds. Average yields of groups of industrial and municipal wells in the so-called shales range from 62 gpm in north-central Pennsylvania to 150 gpm in Delaware County, N.Y. Lower apparent yields in northeastern Pennsylvania are based on too few records to be reliable. Yields of this magnitude, of course, reflect the presence of dominant sandstone beds in what is frequently thought of as a shaly section. The high yields of a few individual wells in northern and eastern Pennsylvania and southeastern New York (pl. 2) suggest that where sandstone beds are liberally intercalated in the otherwise shaly section, the average yield of multiple deep wells utilizing 100 feet of drawdown should be on the order of 150 gpm rather than 100 gpm.

MISSISSIPPIAN AND PENNSYLVANIAN FORMATIONS

The Mississippian formations are largely shales with some interbedded sandstones and the Pennsylvanian formations are largely sandstone with some interbedded shale and occasional limy or coal beds. A yield of 600 gpm with 30 feet of drawdown was obtained from Mississippian sandstone in one locality in Pennsylvania and 832 gpm with

25 feet of drawdown was developed at another locality from Pennsylvanian sandstones.

The highest average yield that can be demonstrated from the records of industrial wells in sandstone, 150 gpm, is from the lowest Mississippian sandstones. This figure is based on the records of 19 wells after making empirical adjustments of drawdown on 13 wells in that group. However, in this area in north-central Pennsylvania, there are also 15 industrial wells located along alluvium-floored valleys that were excluded from the 150-gpm average. The average yield of these excluded wells is 460 gpm, without drawdown correction. With drawdown correction, the average yield of these wells is estimated to be at least 550 gpm. The wells range in depth from 141 to 266 feet in depth.

Yields of this magnitude likely can be obtained only along rivers where ample recharge is available. The occurrence cited illustrates the great difficulty in assigning average yields to any consolidated rock formation. In considering both limestone and sandstone, the source of recharge is of considerable importance. Limestones probably have the more far-reaching channels to draw upon storage and recharge, but where either formation is bracketed by tight rocks such as shales the average sustained yield may be moderate.

The Mississippian and Pennsylvanian sandstones are commonly ridge forming in the belt of folded rocks, and as in older sandstones mentioned previously, the water level in these beds will vary considerably from season to season with consequent effect on well discharges. A well in the Pennsylvanian sandstone in northeastern Pennsylvania is reported to yield 250 gpm with 10 feet of drawdown in the wet season but only 150 gpm with 133 feet of drawdown in the driest part of the year. Where these sandstones lie in the Appalachian Plateaus province to the west of the folded Appalachians, very much less marked variations in yield would be expected from season to season.

Acid waters are uncommon, even in the sandstones that include coal beds. Acid water is produced by the oxidation of sulfide minerals associated with coal, but where these minerals are well below static level, oxidation occurs slowly, if at all. However, water from some wells in sandstone does have a high iron content.

Records of wells in bedrock in industrialized areas of Rhode Island do not differentiate between the formation penetrated. However, by far the greater number of wells seem to be developed in a group of late Paleozoic (Carboniferous) and Devonian metamorphic rocks, such as slate and phyllite, and in some other rock types, such as conglomerate. A few of the Rhode Island wells may be finished in intrusive (granitic) rocks. In southeastern Massachusetts a fairly accurate separation was made of wells developed in granitic rocks from those in metamorphic rocks.

The average yield of 50 wells in the Providence area deeper than 350 feet is 84 gpm. However, wells 200 to 350 feet deep yield about 100 gpm. Obviously some manipulation of the data is necessary to come to a more common sense conclusion regarding the yields of wells drilled to optimum depth. Averaging all wells, both shallow and deep, gives a figure of 88 gpm. Guessing how much more the shallower wells would yield if they had been continued to a depth of 450 feet, we might conclude that a yield of over 95 gpm would be reasonable. The estimate of over 95 gpm can be rounded off to 100 gpm, because at least four of the wells in the group are on unfavorable hilltop locations and the yields of at least five of the wells are limited by the capacity of the pump.

In Bristol and East Greenwich, R.I. (Allen, 1956), the apparent yields in the same general physical situation are much lower. The writer feels that little importance, if any, should be given those data, based on a dozen wells in each area, in the light of much better data at Providence.

The estimate arrived at for wells in southeastern Massachusetts is not greatly lower than what the Providence data indicate, even though the records of only 14 wells were available for averaging. Seven of the wells in the group range from 105 to 210 feet in depth. One of the wells yields 250 gpm with 14 feet of drawdown, but adjustment to 100 feet of drawdown was not made.

TRIASSIC SANDSTONES AND SHALES

Triassic sandstone, shale, and minor conglomerate with intercalated volcanic basalt and intrusive diabase are present as a somewhat narrow discontinuous strip extending from southern New England down through Virginia. Moderately high yields have been obtained from deep wells in areas that have been highly industrialized—central Connecticut, Rockland County in southeastern New York, eastern New Jersey and Pennsylvania, and the Virginia area west of the District of Columbia.

The greater part of the group of formations is made up of sandstone and shale. In Pennsylvania and New Jersey these are mapped separately. The figures given for yields in Pennsylvania are averages obtained for wells drilled in the sandstone. Comparable yields in Rockland County, N.Y., central Connecticut, and Virginia are from undifferentiated Triassic rocks.

The average yield of deep wells in the Triassic lowland of Massachusetts, 65 gpm, contrasts sharply with the result obtained in adjacent Connecticut, 157 gpm. In part, the difference can be explained by the fact that there are fewer industrial wells in Massachusetts. A more widespread group of wells intended to provide a maximum volume of water might have a higher average yield. Following the general rule adopted here, one well in the Massachusetts group that yields 760 gpm has been omitted from the final estimate. If this yield were included, the average would be 110 gpm. The next highest yield in this small group of industrial wells is 125 gpm.

Half of the wells in the Massachusetts group are in shale, which is considered to be a much poorer aquifer than sandstone. However, some of the higher yields are reported from the wells in shale and the differences in lithology do not seem to offer further explanation of the apparent low yields in this area.

The average yield shown for the Triassic in southeastern Pennsylvania, 162 gpm, is that determined from the detailed study of records from Montgomery and Berks Counties. Twenty-five wells in Bucks County (Greenman, 1955) have an average yield of 170 gpm. The highest yield of any well there is 440 gpm. In Lancaster County the average yield of eight industrial wells is also 170 gpm. The highest yield well in that small group is reported to be 330 gpm.

In southern Pennsylvania, nine deep wells in sandstone in Adams and York Counties (Wood and Johnston, 1964) have an average yield of only 23 gpm, whereas 16 wells of intermediate depth have an average yield of 74 gpm. Obviously, here, only the poorer wells have been drilled to maximum depth. The average of all these wells is 56 gpm. If all the wells were drilled to a depth of 450 feet, the average yield would be higher, but perhaps not more than 70 gpm.

Two exceptionally high yield wells in Leesburg, Va., end in a limestone conglomerate. Presumably, this type of rock may be more favorable than the noncalcareous conglomerates.

In northeastern New Jersey, a few deep wells penetrating diabase flows have excellent yield (Nichols, 1968). Here warping of the flows has probably broken up the massive rock to the extent of creating a fairly good aquifer.

In Union County, N.J. (Nemickas, 1970), a group of 117 municipal and industrial wells has an average yield of 300 gpm. The high average yield here is ascribed to the presence of overlying saturated glacial sands.

In places in Pennsylvania and Virginia records indicate that yields of certain wells in the Triassic rocks have declined over a period of years. There are enough such reports, perhaps a dozen, to indicate that diminution of yield with time may be a somewhat common problem of wells in this formation.

Unless there is a regional decline of water level due to limited recharge, diminution of yield is most likely due to swelling of shaly beds in the formation, perhaps because water of a different chemical character from that originally present was drawn into the formation during continuous heavy discharge.

Scrubbing the walls of the well with a wire brush and surging may improve such wells if the swelling of shales is the cause of the trouble and if the swelling is confined to the walls of the hole. If swelling is elsewhere, it seems unlikely that the well can be brought back to its former productivity. Clogging by iron or limy deposits could also bring about a diminution of yield. Here, too, if the clogging is localized on the walls of the well, scrubbing and cleaning may bring about a restoration of original yield.

SPECIAL STRUCTURAL SITUATIONS

Areas of strong faulting should commonly be favorable sites for wells because where brittle rocks are more or less shattered, yields of wells penetrating them may be much higher than elsewhere. (Where shale and plastic schists are involved, yields may not be much greater than in areas that have not been subjected to faulting.) On and along a fault, water may be transmitted along the fault plane as well as through the adjacent shattered rock walls. However, gouge may be present along the fault plane and inhibit movement of water. Commonly, gouge may act as a more or less effective ground-water dam. As exemplified by a well at Beacon, N.Y., a well penetrating gouge may be difficult to stabilize if the gouge is granulated material.

However, the location of optimum well sites is probably near fault zones where rock tends to be more fractured than elsewhere, in preference to other possible sites (pl. 2). The suggestion also applies to minor faults that are offshoots of the major faults shown on most geologic maps.

In western Massachusetts and southeastern New York high-yield wells are located in the Taconic overthrust area. A very high yield well in eastern Pennsylvania situated along the Triassic boundary fault was also mentioned. In Leesburg, Va., a well of exceptionally high yield, 950 gpm, that penetrates conglomerate is located about two-tenths of a mile east of the Triassic border fault. Two test wells that were nonproductive passed through the boundary fault itself and into underlying greenstones. Minor faults mark the Dulles Airport area where a well yielding 1,000 gpm was completed (Johnston, 1960). A fairly high-yield well is present at Culpeper, Va., along the Triassic border fault.

The zone of disturbed carbonate rock at the western foot of the Blue Ridge overthrust is a favorable site for high-yield wells. Large volumes of ground water have been developed at Elkton, Grottoes, Waynesboro, and Roanoke, Va. At Elkton five wells in carbonate rocks located 15 feet apart reportedly yield a total of 8.5 mgd when pumped simultaneously.

Additional data on wells which penetrate fault zones in the North Atlantic region are lacking. However, along some or many of the faults, both mapped and as yet undetected, granites and quartzites must be more shattered than elsewhere, and massive limestones must be broken up; the result is that the openings thus formed are susceptible to enlargement by solution. Hence, many of the fault zones should prove to be sites where especially high-yield wells can be constructed. There is also reason to believe that anticlinal crests (pl. 2) are loci of tension cracks and should be favorable well locations.

In almost any area in the North Atlantic region, faults will be marked by linear topographic depressions. Where the geologic framework is obscure owing to lack of detailed mapping or to heavy overburden, locating wells in conspicuous linear depressions will improve the chances of finding any such fault zones. Such valleys commonly mark zones of minor fissuring that are more favorable well sites than elsewhere.

Looking at the geological framework even more broadly, rocks would likely be more shattered in the folded Appalachian Valley than in the adjacent Appalachian Plateaus province or in lower New York State. Hence, the valley should offer more opportunities to develop high-yield wells than the other two areas mentioned. Wyrick (1968) has shown that many rock types comparable with those discussed above have very low yields in the Plateaus province. Within the North Atlantic region, data at hand are not sufficient to show this difference. Furthermore, possible structural differences are obscured by lithologic differences. For instance, gently tilted Devonian shales of New York are more productive than those in the folded rock area to the south, because in New York the shales are actually somewhat shaly sandstones.

Whether or not massive limestones are less riddled with solution channels in New York State than in Pennsylvania and southward into Virginia cannot be said on the basis of available data.

Synclinal troughs might be better locations for wells than elsewhere because water tends to funnel into them. However, rocks in synclines may be more compressed than in anticlines where upward relief during folding has produced more fractures. In some synclinal troughs in Pennsylvania, deep wells yield somewhat highly mineralized water owing to poor circulation in that zone.

SUMMARY

Absolute values for yields of wells in consolidated rocks cannot be given for several reasons: data on which to base estimates are far from complete, the intensity of folding and faulting (roughly an index of fracturing of the rock) varies considerably from place to place, the physical character of the rocks themselves is not constant from place to place, and the opportunities for recharge of the formations range from very poor to optimum.

Nevertheless, figures presented here are useful for planning purposes. The figures given in table 1 are characteristic of results obtained where enough industrial and municipal wells have been drilled to give a meaningful average.

Some results reflect drilling at slightly better than average locations; as already noted, the wells in granite in Massachusetts and in the Richmond area, Virginia, may be more favorably located with respect to recharge than those in some other areas. On the other hand, the yields for wells in limestones (table 1) may be very low because the wells used in the estimates are not located on fracture traces except by chance. The figures do not reflect results possible in strongly faulted areas or in some areas where recharge potential is especially favorable.

TABLE 1.—*Average yields of wells 350 to 450 feet deep in consolidated formations in multiple-well developments at 100 feet of drawdown*

Formation	*Yield, in gpm*	*Formation*	*Yield, in gpm*
Limestone	300	Schist	90
Sandstone, northern New York	100(?)	Greenstone	25(?)
Sandstone, except northern New York	160	Marble	100
Shaly sandstone or sandy shale	100	Undifferentiated granite and metamorphic rocks, coastal New England	90
Shale	40	Undifferentiated granite and metamorphic rocks, inland New England and New York	50(?)
Slaty shale	75		
Limy shale	75		
Granite	90		
Granite gneiss	50		

Nature has not provided neat homogeneous units of rock having characteristics that are constant even for short distances. Hence, the figures in table 1 should be considered reasonable estimates, with the expectation that figures will vary somewhat for water developments in any one locality. However, a 25-percent margin, above or below the figures given, will suffice for most variations. Where well sites are selected by a hydrologist and as greater understanding of the occurrence of ground water in consolidated-rock formations is gained, some of the average yields given in table 1 may be doubled or tripled.

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Era	FORMATION	VIRGINIA	WESTERN MARYLAND	EASTERN MARYLAND	SOUTH-CENTRAL PENNSYLVANIA	SOUTH-EASTERN PENNSYLVANIA	NORTH-CENTRAL PENNSYLVANIA	NORTH-EASTERN PENNSYLVANIA	EASTERN NEW JERSEY	SOUTH-EASTERN NEW YORK	EASTERN NEW YORK	NORTHERN NEW YORK	WESTERN MASSACHU-SSETTS	SOUTH-EASTERN MASSACHU-SSETTS	CONNECTICUT	RHODE ISLAND	MAINE
MESOZOIC	Triassic sandstones and shales	[a] 157 (25) (600-955)151				162 (111) (395-300)18			300 (117) (870-400)73	[b] 192 (65) (675-252)			[c] 65 (16) (125-407)		157 (76) (510-600)105		
PALEOZOIC	Pennsylvanian sandstones with interbedded shale and coal measures		(75-250)8 (220-200)	75 (12) (300-1276) (300flow-831)	100 (10) (250-175)15 [d] 75? (8) (150-120)61 150 (31) (832-107)25		(250-200) (150-203)20	(80 150)12 95 (15) (160-566)115									
PALEOZOIC	Mississippian shale and subordinate sandstone in upper part of section and sandstone with subordinate shale in lower part		(130flow-257)	(65-250)	(400-365)65 (100-83)15		150 (19) (600-237)30	110 (47) (375-600)115 (133-800)40						PALEOZOIC METAMORPHIC ROCKS 75 (14) (250-504)14		[e] 98+ (57) (320-500) 46 (12) (100-477) 64 (12) (150-504)	(140-151)
PALEOZOIC	Upper Devonian shale, sandy shale, and sandstone		(57-380)40	25? (44-605)	(40-300) (80-300)100 (15-260)30		[f] 62 (30) (300-311) [f] 73 (31) (250-247)47	75 (53) (320-285) 38 (7) (89-266) 48 (8) (75-190)		150 (22) (550-140)	90? (4) (150-245)						
PALEOZOIC	Middle Devonian shale and subordinate sandstone		(24-200)40	25 (50-118)			(100+-153) (300-186)	110? (5) (100-335)28				(40-204)					
PALEOZOIC	Devonian Limestone				[g] (40-385)20		[g] (100-108)			[h] (200-275)		[i] (300-386)					
PALEOZOIC	Devonian Sandstone			(200-440)	(250-212)60		(400-244)50										[i] 150 (28)
PALEOZOIC	Devonian to upper Silurian massive limestone			(400-550) 85? (170-194)	(380-313)115 (500-100)			(250-360) (185-202)									(355-300)40 [j] (90-418)8
PALEOZOIC	Silurian limy shale grading down to sandy shale and sandstone	[k l] (300-115)		(175-952)	[l] (386-496)		(160-80+)	75 (11) (130-302)small 100? (12) (200-227)		[m] 60? (150-787)		(150-153)					
PALEOZOIC	Ordovician shale and minor sandstone	(50-155)29		(50-120)	(60-240)200	90 (33) (250-350)				[n] 50 (18) (135-300)	(60-160)						
PALEOZOIC	Ordovician to Cambrian massive limestones	(140-801) (150-244) (300-360) (1200-260)10		150 (16) (385-305)66 82 (8) (370-300)150	(500-301)50 (500-365) (375-305)57	(160-402) 120+ (13) (500-42)'0' 350 (43) (1450-1020) 840 (30) (1800-130)				[o p] 55 (17) (220-228)40 [o j] (37-220)97	(2000-361)	300? (400-416)	[o q] 250 (17) (803-462) [o r] (485-726)31				
PALEOZOIC	M. Cambrian shale	(64-363)20															
PALEOZOIC	L. Cambrian carbonates	(2950-960)		(300—87)													
PALEOZOIC	Lower Cambrian sandstone, shale, slate, and quartzite	[l s] (45-236)'0'		50 (6) (103-720)18	[s] (Large-300)	[s] (225-225)											
PRECAMBRIAN	Granite	[t] 90 (44) (380-600)94		50? (4) (100-226)		(75-200)				[f] 30+ (15) (75-180)				[u] 90 (18) (150-189)½			(150-85)
PRECAMBRIAN	Granite gneiss					40 (8) (100-100)				[f v] 35+ (29) (80-80)				VARIOUS AGES	(80-122)100		
PRECAMBRIAN	Schist	100 (24) (275-451)2+		100 (15) (300-140)		80 (31) (250-500)				[w] 65 (47) (280-166)61			(100-87)		(100-200)		(100-208)
PRECAMBRIAN	Greenstone	25? (3) (35-360)	50 (9) (160-161)10							(200-600)							
PRECAMBRIAN	Marble			100+ (12) (200-695)30		(110-69)				90 (19) (300-300)							

EXPLANATION

157
Average yield, in gallons per minute

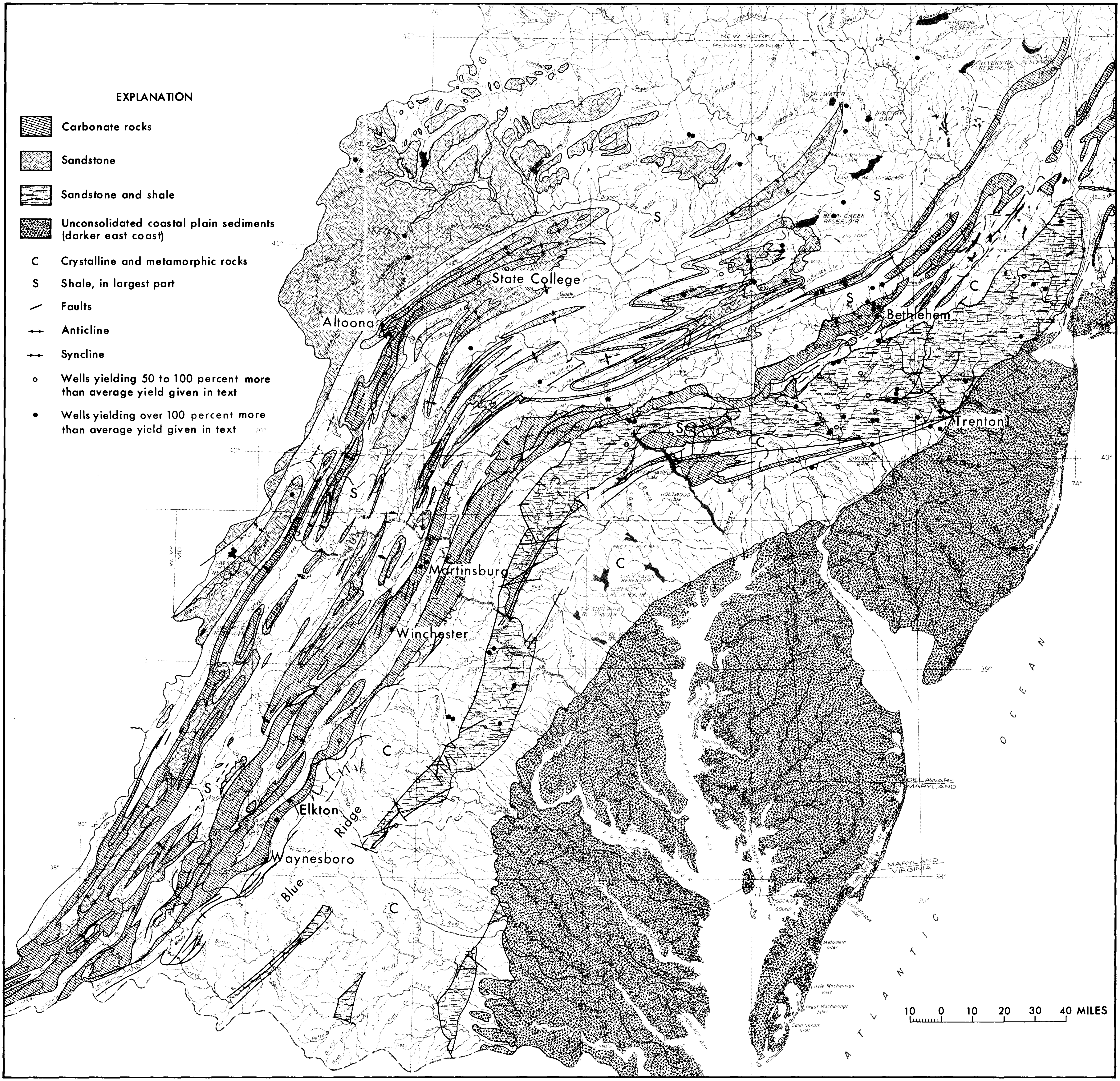
(25)
Number of samples in the average

(600-955)151
Yield (gpm), depth (ft), and drawdown (ft) of the highest yield well in the sample

a. Greater Washington, D. C., area. Two wells yielding 1,000 and 950 gpm excluded from the average.
b. A well yielding 1,515 gpm excluded from the average.
c. A well yielding 760 gpm excluded from the average.
d. Wells shallow.
e. In descending order, average yields at Providence, Bristol, and East Greenwich, R. I.
f. Many wells shallow.
g. Limy shales.
h. Shaly limestone.
i. Limestone.
j. Slaty or quartzitic rock.
k. Berkeley County, W. Va.
l. Well in sandstone.
m. Seneca County, N. Y. Some wells in Seneca and Wayne Counties, N. Y., yield brackish water.
n. Slaty shales, Dutchess County, N. Y.
o. Taconic sequence.
p. More than half the wells are shallow.
q. Two wells yielding, respectively, 1,400 and 1,600 gpm excluded from the average.
r. Quartzite.
s. Shale.
t. Richmond, Va., area.
u. A well yielding 500 gpm omitted from the average.
v. A well yielding 365 gpm omitted from the average.
w. A well yielding 400 gpm omitted from the average.

CHART SHOWING SUMMARY OF DATA ON WHICH ESTIMATES OF YIELDS OF DEEP WELLS IN CONSOLIDATED ROCKS ARE BASED, VIRGINIA TO MAINE

468-129 O - 72 (In pocket) No. 1



Geology from geologic maps published by the States of New Jersey, Virginia, Pennsylvania, and Maryland

MAP SHOWING LOCATION OF HIGH-YIELD WELLS IN CONSOLIDATED ROCK FORMATIONS WITH REFERENCE TO GEOLOGIC STRUCTURES IN THE APPALACHIAN HIGHLANDS FROM PENNSYLVANIA TO VIRGINIA

468-129 O - 72 (In pocket) No. 2