Cost Analysis of Ground-Water Supplies in the North Atlantic Region, 1970

By D. J. CEDERSTROM

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By D. J. CEDERSTROM

ABSTRACT

The cost of municipal and industrial ground water (or, more specifically, large supplies of ground water) at the wellhead in the North Atlantic Region in 1970 generally ranged from 1.5 to 5 cents per thousand gallons. Water from crystalline rocks and shale is relatively expensive. Water from sandstone is less so. Costs of water from sands and gravels in glaciated areas and from Coastal Plain sediments range from moderate to very low. In carbonate rocks costs range from low to fairly high.

The cost of ground water at the wellhead is low in areas of productive aquifers, but owing to the cost of connecting pipe, costs increase significantly in multiple-well fields. In the North Atlantic Region, development of small to moderate supplies of ground water may offer favorable cost alternatives to planners, but large supplies of ground water for delivery to one point cannot generally be developed inexpensively. Well fields in the less productive aquifers may be limited by costs to 1 or 2 million gallons a day, but in the more favorable aquifers development of several tens of millions of gallons a day may be practicable and inexpensive.

Cost evaluations presented cannot be applied to any one specific well or specific site because yields of wells in any one place will depend on the local geologic and hydrologic conditions; however, with such cost adjustments as may be necessary, the methodology presented should have wide applicability. Data given show the cost of water at the wellhead based on the average yield of several wells. The cost of water delivered by a well field includes costs of connecting pipe and of wells that have the yields and spacings specified. Cost of transport of water from the well field to point of consumption and possible cost of treatment are not evaluated.

In the methodology employed, costs of drilling and testing, pumping equipment, engineering for the well field, amortization at 5⅛ percent interest, maintenance, and cost of power are considered.

The report includes an analysis of test drilling costs leading to a production well field. The discussion shows that test drilling is a relatively low cost item and that more than a minimum of test holes in a previously unexplored area is, above all, simple insurance in keeping down costs and may easily result in final lower costs for the system.

Use of the jet drill for testing is considered short sighted and may result in higher total costs and possibly failure to discover good aquifers.

Economic development of ground water supplies will depend on obtaining qualified hydrologic and engineering advice, on carrying out adequate test drilling, and on utilizing high-quality (at times, more costly) material.

INTRODUCTION AND ACKNOWLEDGMENTS

As a participant in the North Atlantic Water Resources Study headed by the U.S. Army Corps of Engineers, the U.S. Geological Survey had the responsibility of evaluating the cost of producing ground water in the North Atlantic Region (fig. 1). Data obtained during this evaluation, taken in conjunction with broad assessments of quantities of ground water available, will assist planners in deciding which of two or more alternative sources of supply might best be developed or where combinations of alternative sources might be desirable.

The overall study was directed by Mr. Harry Schwarz, chief, North Atlantic Study Group, U.S. Army Corps of Engineers. The writer worked under the immediate supervision of Mr. George E. Ferguson, regional hydrologist, Atlantic Coast Region, U.S. Geological Survey. Their interest and encouragement are greatly appreciated. Several drilling firms gave assistance on market costs without which this report could not have been written. These are Sydnor Hydrodynamics Co. of Richmond, Va.; Stephen B. Church Co. of Seymour, Conn.; R. E. Chapman Co. of Oakdale, Mass.; Green Mountain Artesian Well Co. of Putney, Vt.; and Layne-New England Co. of Arlington, Mass.

PURPOSE AND SCOPE

The purpose of this report is to show the methods of calculating costs of ground-water supplies for municipal and industrial uses from the various aquifers in the North Atlantic Region and the range in costs of the supplies. The capital cost of ground water and the cost per thousand gallons in typical geologic and hydrologic environments are given in tabular form and graphs.

As developed for broad planning purposes, the approach taken in this report is that large areas may be generally characterized as to range of yields per well and that the material and work needed to construct wells with those yields can be estimated within reasonable limits. Thus, in areas where ground water is obtained from consolidated rock, average yields of production wells may ordinarily range from 75 to 300 gpm (gallons per minute) depending on the type of aquifer (although exceptions are not uncommon); and, depending on yields obtained, costs should work out somewhat as shown in appropriate tables and graphs. The yields given are those generally obtained in the North Atlantic Region. Where very small yield or exceptionally large yield wells are considered, costs may be worked out according to the methodology described below. It follows that the ranges of values given enable a hydrologist to approximate the cost of water from wells of

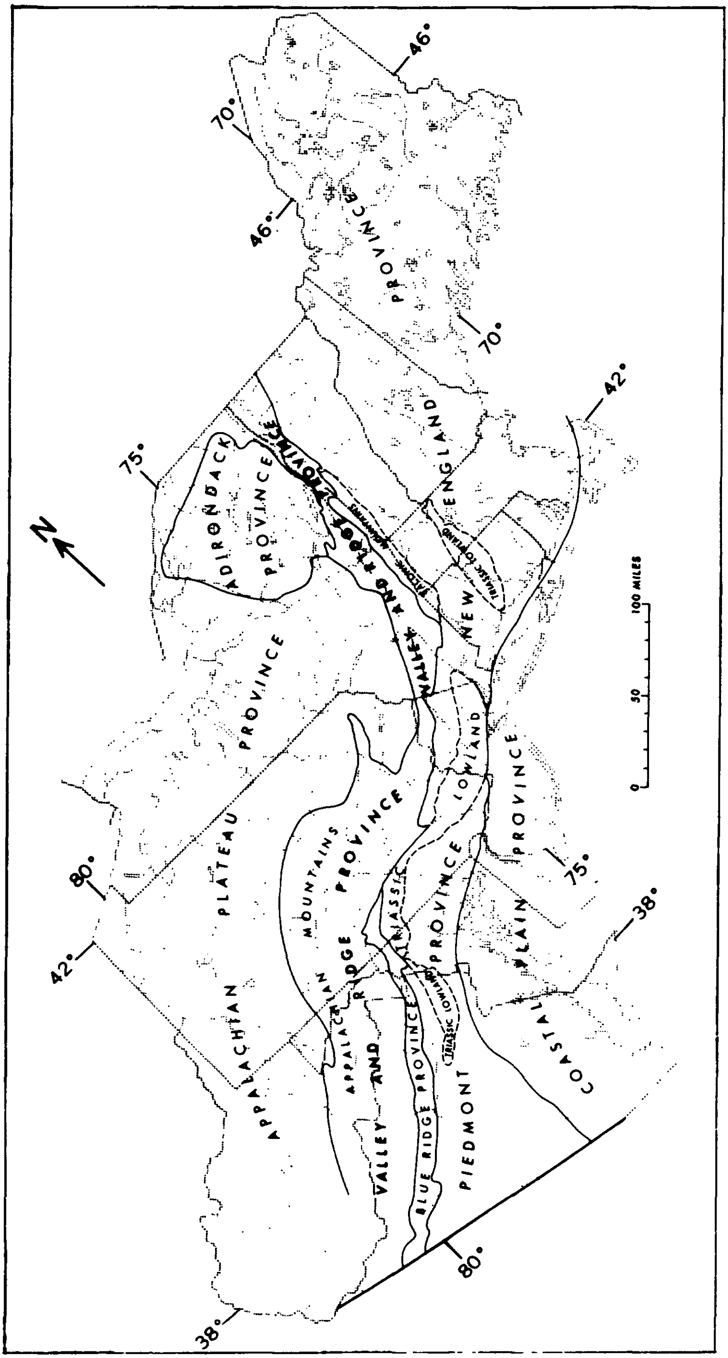

FIGURE 1.—Physiographic provinces in the North Atlantic Region.

various yields, and from well fields containing a few or many wells, but only after a geologic and hydrologic assessment has been made insofar as any specific locality is concerned.

Still another objective of the report is to show the relative unimportance, in terms of final cost per thousand gallons to the consumer, of additional (or more than minimal) material or development costs incurred during construction. It is shown that skimping on capital costs is poor economy, while on the other hand small or moderate increases in capital costs for critical items may result in real economies in the cost of water produced.

As discussed in detail below, the elements that must be considered in arriving at costs are (a) the probable yield of wells in various geologic environments, (b) the cost of drilling and equipping the wells for production, (c) the spatial distribution of wells relative to rate of recharge per square mile, (d) the cost of interconnecting pipeline in multiple-well developments, and (e) amortization of capital costs and assignment of maintenance and pumping costs, all of which refer to a series of calculations of cost of water per thousand gallons delivered at the wellhead or from a well field consisting of two to as many as 40 wells.

In assembling basic data and evaluating costs of test- and production-well drilling, it became apparent that a clear understanding of costs is highly pertinent for the hydrologist who is conducting a ground-water test and development project. Briefly, test drilling is a low-cost item and a production well field is, relatively, a high-cost item. The number of test holes that should be drilled can best be determined by the hydrologist, who can weigh the cost of additional test holes against the possible gains in higher yielding production wells. The data presented here are intended to enable him to make such assessments.

RELATIONSHIP OF GROUND WATER TO SURFACE WATER

To put present ground-water developments in proper perspective, well discharge in the North Atlantic Region is of the order of magnitude of a drop in the bucket. Deleterious effects on streamflow have been demonstrated in a very few places, whereas the convenience and economy of tens of thousands of well installations is readily apparent. However, when extensive development of the overall water system is contemplated, that is, ground water as well as surface water, the intimate relationship of the two sources and the net gain achieved by reduction of evapotranspiration loss will have to be thoroughly understood and carefully considered for optimum results.

In some geologic environments a discharging high-yield well will induce a flow of water from a nearby river (fig. 2) to the well,

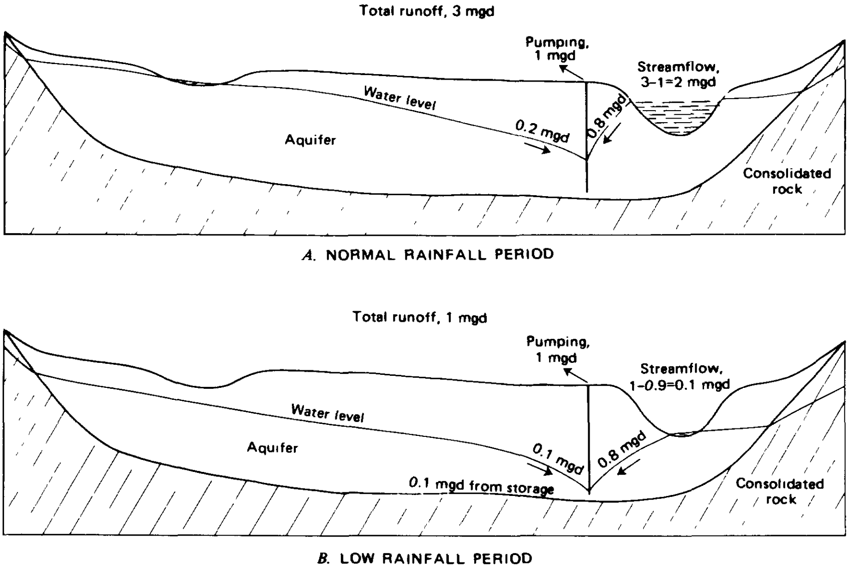

FIGURE 2.—Effect on streamflow of a pumping well close to a stream. Pump discharge is almost entirely stream water and streamflow is seriously affected in the low rainfall period (*B*).

the aquifer thus merely performing the function of a pipeline to the river, but, if the well is developed in a sandy aquifer, with the added advantage of delivering filtered water. However, the ground-water discharge in such areas is not an addition to the available supply. Further, where only small streams are nearby, a large ground-water development may have the effect of drying up those streams, an effect that may or may not be desirable. Wells distant from a stream may not induce a flow from the stream, but will capture water ordinarily flowing to the stream. In most areas, this loss to the stream may be a small price to pay for availability of water at or near the point of use and in any event may merely be a substitute for running a pipeline to the stream itself.

There are other circumstances, however, where development of ground water is not necessarily a subtraction from total available water in a basin. Management procedures based on sound hydrologic principles can take advantage of ground storage and the variations in the flow of streams in many places (fig. 3). Briefly, where ample ground storage is available, wells somewhat distant from large streams or rivers may be pumped in times of low flow without having any great effect on streamflow at that time. Ground storage will be depleted to a greater or lesser extent, but because there is a lag in time for the cone of depression around the

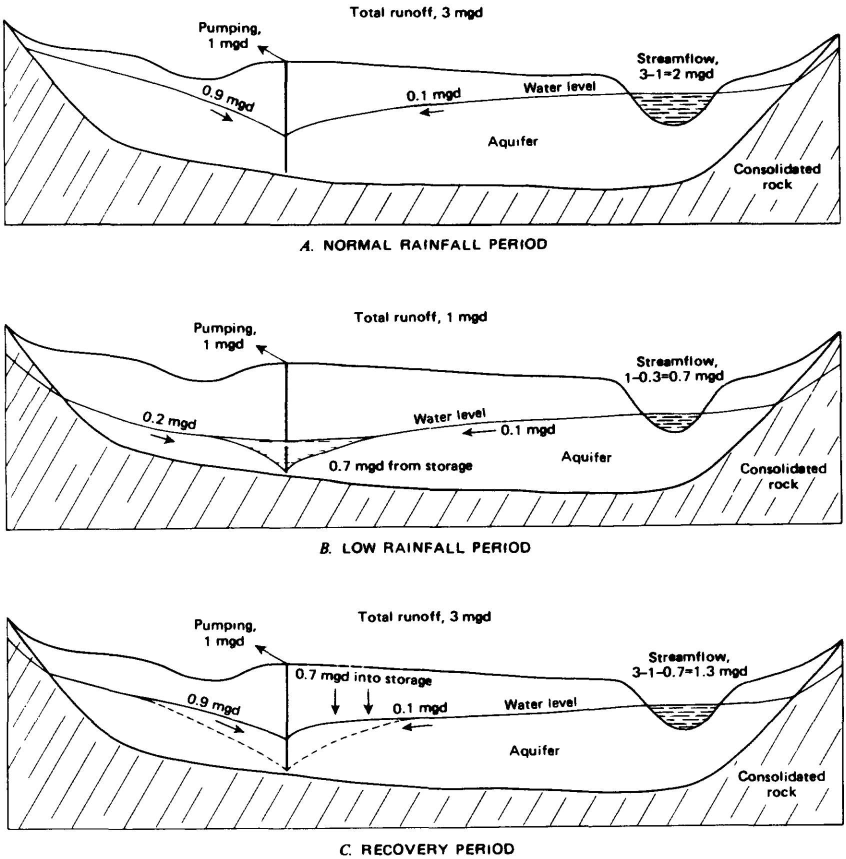

FIGURE 3.—Effect on streamflow of a pumping well distant from a stream. Streamflow in the low flow period (*B*) is only slightly affected because much of the ground water pumped is from storage. The deficiency in storage is made up in the succeeding higher rainfall and higher streamflow period (*C*).

pumping wells to reach the stream, most of the consequent reduction of streamflow will come at the succeeding high-flow period when "excess" water is available. Thus, the utilization of ground storage at time of low flow provides additional available water at the time of minimum streamflow supply.

In Coastal Plain deposits, much of the water pumped from artesian wells is salvaged water—water that would otherwise flow generally eastward past the well field—and it is therefore a contribution to the total available supply. In fact, where leakage downward from the surficial sands is induced by heavy pumping of artesian wells, there is the additional gain of water that is presently almost entirely wasted. Diminution of brooks and streams in the North Atlantic Region resulting from such leakage would probably be slight in most situations.

GEOLOGIC FRAMEWORK

In the North Atlantic Region, crystalline rocks, largely granite, schist, and gneiss, make up the Piedmont, New England, and Adirondack provinces (fig. 1). These are poor aquifers in most places and not susceptible to development of large ground-water supplies. The Triassic Lowland, made up of shale, sandstone, and associated volcanic rocks, lies within the crystalline-rock areas. In New England the Triassic formations dip eastward, but from southern New York to Virginia they are inclined to the west. Moderate supplies of ground water have been obtained from Triassic rocks in many places. The Valley and Ridge province and the Taconic Mountains are made up of folded and faulted shales, sandstones, and carbonate rocks (limestones and dolomites). Large supplies of ground water have been developed in these provinces, particularly from the carbonate rocks where structural deformation has been intense. Sediments similar to those in the Valley and Ridge province are present in the Appalachian Plateau province, but there they are very gently tilted to the west. Yields of wells in the Plateau province appear to be much the same as in the less structurally disturbed parts of the Valley and Ridge province.

The Coastal Plain sediments consist of an alternating succession of clays and sands, the latter ranging from fine to coarse in texture. Where they lap against the Piedmont rocks (the Fall Zone) they are thin, but eastward the Coastal Plain sediments thicken to 8,000 feet or more at the Atlantic shore. Relatively small supplies of ground water can be obtained from wells along the Fall Zone, but from 5 to 15 miles east of the Fall Zone, large supplies are generally available. Water occurs under artesian conditions in largest part. Still farther eastward wells in the artesian beds yield brackish or salty water.

Glacial deposits in the North Atlantic Region extend as far south as Long Island and central Pennsylvania. Insofar as municipal and industrial water supplies are concerned, only the water-laid sands and gravels, generally confined to present river valleys and water courses, are important. Yields range from very small to very large. Where infiltration from major rivers can be induced, large supplies can be obtained from relatively shallow, closely spaced wells.

METHOD OF CALCULATING COSTS

METHODOLOGY

The first step taken in estimating costs of ground water in the North Atlantic Region was to decide upon the dimensions of a representative series of wells in the three main aquifer types, the equipment necessary for a complete installation, and the work required to complete a well as a production unit. The design of the wells and the costs of equipment and work performed was established on the basis of advice given by leading drillers in the region.

Material and work costs plus an engineering and contingency fee were added to give the capital costs of wells of various dimensions and yields. The capital costs of individual wells were then amortized by applying an appropriate factor, as will be explained below, giving the annual amortization cost. The annual maintenance cost was added to the annual amortization cost to give the total annual cost of the installation. This annual cost figure was reduced to a daily cost figure. The daily cost divided by the number of thousands of gallons of water delivered then determines the cost per thousand gallons insofar as the well and pump installation is concerned. (The daily discharge used in these calculations was only 60 percent of the reported yield of the wells, as given in the tables.) The cost of power was added to the previously calculated costs to obtain total cost per thousand gallons at the wellhead.

A similar calculation was made for costs of connecting pipe in multiple-well fields. Figure 4 shows the cost of the pipe needed for a range of flow values. According to various spacings selected and data from the graph, the cost of the pipe was calculated, to which was added costs of easements. That sum was amortized, maintenance cost added, and the total reduced to costs per thousand gallons and listed in the tables in the column "Added pipe cost." The cost of water per thousand gallons at the wellhead determined in the preceding calculation is shown again in the pipe cost tabulations where the system consists of only one well. That wellhead cost is added to the pipe costs to obtain the total costs per thousand gallons.

PRICE LEVELS

The capital costs shown for drilling operation and necessary equipment for completing producing wells were based on generalized market costs as of 1968 as obtained from drilling firms in Massachusetts, Connecticut, and Virginia. These were raised by 10 percent to approximate 1970 costs.

DRILLING

It was necessary to make several assumptions upon which to base estimated costs. These assumptions are described in the following paragraphs.

It was assumed that in consolidated rock, down-the-hole hammer (air-rotary) drilling equipment would be used. Two 5-inch-diameter holes are drilled to a depth of 400 feet, one of which is assumed to be successful in producing the desired amount of water (Seaber, 1966). The successful well is reamed to a depth of 125 feet and to a nominal diameter of 8 inches to accommodate the pump.

In glacial sand, provision is also made for one unsuccessful hole in locating and constructing each production well (In some areas the search for narrow stringers of glacial sands may require several test holes. In such places, appropriate adjustments of cost figures given here must be made.) Only the highest yield wells are completed with larger diameter casing in the upper part of the hole, down to a level below the probable pump setting.

In Coastal Plain sediments, results of drilling near the Fall Zone are somewhat erratic, and one unsuccessful hole is provided for each production well at 150 gpm. East of the Fall Zone, wells are successful in most areas, and no provision is made for an unsuccessful test hole.

Casing diameters selected for the upper part of the hole are those recommended for the setting of pumps (Johnson, 1966, p. 186). In glacial and Coastal Plain sediments, the lower length of casing is of sufficient diameter to accept the optimum size of screen. In some wells, depending on the type of pump used, smaller diameter casing may be used in the upper part of the hole.

It is not inferred that any particular type of equipment is best for drilling any particular type of earth material. Cable-tool rigs, for example, have been and are presently used in hard rock and in glacial and Coastal Plain sediments with success, and the jetting method is commonly used today in the Coastal Plain for smaller diameter wells.

Variations in drilling costs from place to place are likely, but even where costs are somewhat different from those shown, the net result (that is, the cost per thousand gallons) will not be greatly different from that given in the tables. For example, in table 7, the cost of water from a 300-gpm well in consolidated rock is shown to be $0.0219 per thousand gallons at the wellhead. If the capital cost of the well were $2,000 greater than the $14,926 shown, the cost per thousand gallons would work out as $0.0239 instead of the $0.0219 given in the table, a difference only of 2 mills per thousand gallons. Therefore, estimates arrived at for cost per thousand gallons will be generally applicable even though expected variations from the basic cost figures do occur.

DEVELOPMENT

No allowance is made for development of wells drilled in consolidated rocks because development will ordinarily occur as the holes are drilled and formational water is discharged. Development of rock wells (wire-brush scrubbing and rawhiding) is desirable in low-yield rock wells but may not be necessary in higher yield wells where water enters the well through larger openings.

Development costs are given for wells in glacial and Coastal Plain deposits that are finished as "naturally developed" wells without gravel packing. The higher yield wells are considered to require as much as 4 days' development work. Although some wells finished in granular sediments seemingly develop quickly, it is likely that the development indicated is desirable to insure maximum production and stability of the well.

PUMP

The pump selected, in every well, is a submersible pump set at 125 feet that will deliver quantities stated at a maximum head of 200 feet. Included with the pump are riser, cable, magnetic starter, check valve, and gate valve. Cost of installation is also included.

Obviously, a 125-foot pump column could not be installed in some of the wells with the dimensions given (table 11), but the cost difference between the dimension selected and a shorter column is small, and this difference was ignored.

SCREENS

Screens installed in wells in glacial deposits and Coastal Plain sediments are designed to permit entrance of the volumes stated at a recommended entrance velocity of 0.1 foot per second (Johnson, 1966). Costs of screen include fittings and $110.00 for setting the screen.

PUMP TEST

A capacity test is provided for completed wells, as long as 4 days in duration for the highest yield wells. In some few wells the test run allowed for may be made by the municipality or by the industry staff after installing the permanent pump.

No provision is made for observation wells for aquifer testing to determine optimum spacing of wells, entrance losses, or other factors.

HOUSE AND LOT

The cost of a lot is assumed to be $1,000 (plus 10 percent) although it is likely that in many places the well may be on public property or on company property and the cost of a lot will not be applicable.

The wellhouse is considered to cost $1,500 (plus 10 percent). In some areas this cost may be much less.

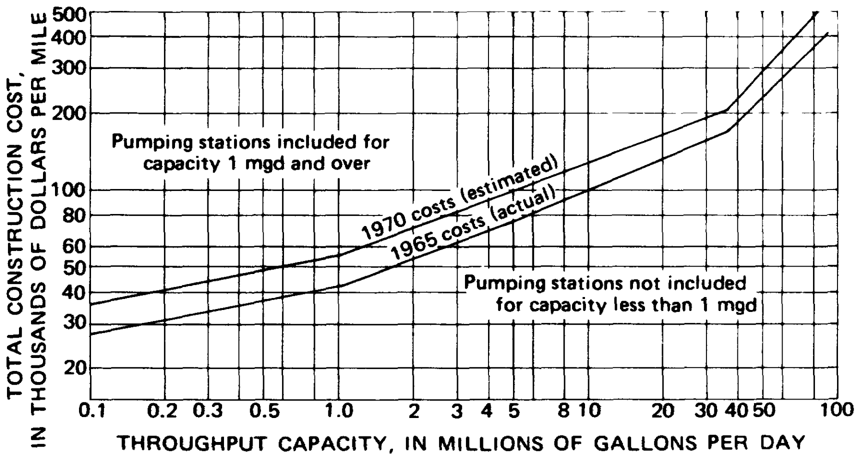

FIGURE 4.—Pipeline construction costs. From U.S. Department of the Interior (1966).

CONNECTING PIPE

Pipe costs are calculated from data given in a graph (fig. 4) shown in Office of Saline Water Research and Development Report 257 (U. S. Department of the Interior, 1966). The graph is based on data submitted by the firm of Lockwood, Andrews and Newman to the Texas Water Development Board in 1965, and on a report by the firm of Black and Veatch, submitted to the Office of Saline Water in 1963. To bring costs to the 1970 level, costs given in the publication referred to were increased by one-third, as shown in figure 4.

In the various well-field plans shown in the tables, the cost of connecting pipe is selected for pipe large enough to carry the full capacity of all the wells in either direction along the trunkline. If the pipe were graduated in size from one end of a well field to the other, costs of the trunkline would be about 55 percent of those shown.

Where a well field consists of a trunkline and laterals, as in figure 6, laterals are only large enough to deliver the output of one well to the trunkline.

The series of calculations for costs of connecting pipe are applicable where a new well field is to be established and a complete system is to be built. Obviously many additions to existing systems will be constructed in the future, and in such places advantage will be taken of pipe already in the ground. Costs of, say, three or four new wells may work out as little more than multiples of single-well costs, rather than the cost of a 3- or 4-well system with connecting pipe as shown in the tables.

As brought out in more detail in the discussion of each of the three types of aquifers considered, well spacing, and therefore pipe costs, is based on certain conservative assumptions of recharge. It may be found in many places that little or much more recharge is available than assumed here. Where this is true, wells may be more closely spaced and pipe costs will be less than given here.

In other situations where, say, 10 wells are to be constructed, two separate well fields might be developed. Costs would then be calculated as those applicable to a 6-well field and a 4-well field, perhaps, rather than to a 10-well field.

Transmission line from the well head, or from the well field to the point of use or to a system of mains, is a cost item that must be considered separately. Cost of transmission from the well field is not included here because of the great variations in that item. The transmission line might be a few hundred feet long or several miles long, depending on the site situation. In comparing costs of ground-water supply with that of an alternative surface-water supply, transmission costs must be determined for water from both sources in order to arrive at a realistic cost comparison.

EASEMENTS

Cost of right-of-way is considered to be $500 per mile.

POWER

Power is assumed to be available at 1 cent per kilowatt hour. At 200-foot head, the cost of pumping is $0.009 per thousand gallons (Johnson, 1947; Illinois State Water Survey, 1968). In the assumptions made in this report, pumping head will be generally less than 200 feet. However, the delivery of water to a storage facility will ordinarily require applied pressure in addition to that necessary to lift water in the well to the surface of the ground, hence, the power cost used may represent a good generalized figure.

ENGINEERING AND CONTINGENCY COSTS

An engineering cost of 15 percent and a 10 percent contingency cost are applied to the capital cost of wells. These percentages are intended to cover an appraisal by a hydrologist, and such professional inspection of the drilling and development operations and of the test run as may be needed.

The data pertaining to pipeline costs used here (fig. 4) include a 25-percent assessment for engineering and contingency. Hence, in the tables given later, engineering and contingency costs are shown as separate items only in the costs of wells.

AMORTIZATION

The Grant and Ireson (1960) capital-recovery equation was used to determine annual payments necessary to cover interest on the initial cost of well installations and payments to a depreciation fund over a 25-year period. On the basis of money borrowed at 5⅛ percent annual interest, the factor is 0.0718. Annual payments then simply become capital costs multiplied by that factor.

MAINTENANCE

It was estimated that 1 percent annum of total capital costs would be ample to provide for maintenance of the wells. Maintenance of pipeline is taken as the standard 0.25 percent per annum of capital cost of the pipeline.

MAXIMUM SYSTEM CAPACITY AND DAILY DISCHARGE

In cost tables in this discussion, the maximum yield of individual wells and the capacity of a system of multiple wells are based on discharge as determined from relatively short term pumping tests. However, a lesser "daily discharge" is listed that is only 60 percent of the "maximum system capacity."

If a well has a yield of, say, 300 gpm as determined from a short-term pumping test, that yield may decline somewhat in periods of protracted dry weather during which there is negligible local recharge and water level declines. Assigning a sustained yield ("daily discharge") of 60 percent or 180 gpm to such a well is probably sufficient to compensate for the lower yields that might be obtained during these infrequent periods of diminished recharge and greater reliance upon ground storage.

CALCULATION OF COSTS PER THOUSAND GALLONS

The cost of water per thousand gallons at the wellhead is calculated by (1) multiplying the costs by the amortization factor to find the annual amortization charge (which amortizes the capital costs of completing the well, maintaining the equipment, and replacing the equipment as needed), (2) adding the annual maintenance charge to obtain the total annual cost, (3) dividing the total annual cost by 365 to find the daily cost, and (4) dividing that cost by the number of thousands of gallons pumped per day. To this is added the cost of pumping the water, $0.009 per thousand gallons.

Where multiple-well discharge is considered, the cost of connecting pipe is determined for various combinations and that cost amortized and charged off on the basis of water delivered, as is done with the well installation. The cost per thousand gallons for pipe is then added to the cost of the water at the wellhead.

The cost per thousand gallons at the wellhead from a single well and the cost at the wellhead from three wells, each of which produces as much as the first well, is the same. Capital costs are three times as great, but the daily discharge is also three times as great and, therefore, the cost per thousand gallons is the same. As the number of wells in a unit increases, the only added cost per thousand gallons is the cost of the connecting pipe. Were it not for the added cost of connecting pipe in multiple-well fields, the lower curve (cost per thousand gallons) in the graphs (figs. 5, 7, and 8) would be horizontal regardless of the number of wells in the system, although the capital costs curve would slant upward as the number of wells in the system was increased.

Moderate adjustments of capital costs as given here will make no significant difference in the calculation of the cost of water to the consumer. Increasing the capital costs of pipe, or any other item, represents the investment of that much more money, but when the increased expenditure is amortized over a period of 25 years and scaled to the cost per thousand gallons, the consumer who is paying for the water on his monthly water bill will find the increased cost negligible. This topic is dealt with in more detail below.

APPLICABILITY OF COST ESTIMATES

The cost figures are somewhat generalized and cannot be applied to particular site situations in view of several factors other than recharge per square mile and average yields of wells upon which these cost calculations are based. These other factors are (a) susceptibility of recharge by streams in or outside the well field, (b) ground water percolating into the well field from outside the block of ground assumed to be the recharge area or, conversely, failure to capture all the recharge in that assumed area, (c) a greater rate of annual recharge when water levels are depressed by pumping, (d) smaller ground-water outflow to the stream system when the water-table gradients to the streams are lowered as a consequence of pumping from wells, (e) capture of evapotranspiration in and around an operating well field, (f) possible reuse of water pumped, and (g) very great differences in the permeability of any one rock type, at least locally.

As given here, the average well in limestone is considered to yield 300 gpm, but in Lehigh County, Pa. (Wood and others, 1970), it appears that it should be possible to develop wells that will yield 1,000 gpm.

In Westchester County, N.Y. (Asselstine and Grossman, 1955), a well in schist is reported to yield 400 gpm where 90 gpm or less would be expected in that formation. Here cost at the wellhead would be about 2 cents per thousand gallons instead of about 6½ cents for a well field consisting of multiple wells and connecting pipe.

Conversely, in some areas where drilled wells may produce less than the average yields listed in table 5, costs would be higher than given here.

It is not possible to state that a well in any one type of formation will yield exactly so many gallons a minute; hence, it cannot be said that water from wells in any formation will cost so much per thousand gallons. Rather, the approach has necessarily been that if a well in glacial deposits or some other formation yields 100 gpm and if the capital costs, the amortization rate, and the maintenance costs are much as stated, then the cost per thousand gallons will be about as given in the tables and shown on the graphs. With increasing number of wells in the system, the costs rise sharply at first, owing to the cost of connecting the wells by pipe and delivering the water to a common discharge header. Thus, the data presented here may be of greater value after a preliminary assessment of a proposed site has been made. A skilled hydrologist can give an estimate of *probable* average yield of multiple wells in the area selected, and a developer can use that estimate to arrive at a *probable* capital cost and cost per thousand gallons of water. Broad ranges of obtainable yields in Coastal Plain and glacial sediments are given in the text. These data simply cannot be used to arrive at an idea of final costs without some knowledge of site conditions. Wells in those formations may yield almost no water if improperly located, but on the other hand may yield 2 million gallons a day or more, per well, if drilled in favorable parts of the aquifer.

Site studies are necessary to arrive at yield and cost figures that take into account all relevant factors in any one specific locality. In this respect, ground-water hydrologists should be called upon to advise on well locations in order that all geologic and hydrologic factors affecting the sustained yield of a well are considered and that costs are brought down to the minimum possible in the geologic-hydrologic environment being developed.

Although not applicable to any specific site, the cost estimates given here have served the broad planning purpose for which they were intended and should be useful in other contexts. It is pointed out that the generalized cost figures given were developed from a study of the North Atlantic Region and may not reflect physical or economic factors determining costs in other areas.

However, the same methods of determining costs can be used in other areas and the discussion of the relationships of gross costs in a test-drilling program leading to a production-well system will be applicable in almost any situation.

THE COASTAL PLAIN AQUIFERS

AVAILABLE SUPPLIES

The Coastal Plain formations consist of a series of sand, gravel, and clay beds that dip gently seaward. They are thin along the Fall Zone, but thicken to 5,000 feet or more along the Atlantic coast.

The surficial sands are thick and somewhat coarse in Long Island, New Jersey, Delaware, and eastern Maryland. Water in rather large quantity can be obtained from them by wells generally less than 500 feet deep. Yields of individual wells may be high, as much as 2,000 gpm, where the greater thicknesses of coarse material are present. In the western part of the Coastal Plain in Maryland and Virginia, the surficial sands are thin and yields of individual wells are low.

The deep artesian beds of the Coastal Plain are among the best aquifers in the North Atlantic Region. Wells range up to 1,000 feet in depth, and yields of over 2 mgd (million gallons a day) may be available in many places, generally 10 or more miles east of the Fall Zone. (The initial yield of an artesian well at Franklin, Va., was 4.5 mgd.) At varying distances seaward the deep artesian beds contain brackish water. Large quantities of water should not be developed close to the fresh water-brackish water boundary in most circumstances. In such areas development of large quantities of ground water will best proceed by stages, with aquifer response carefully noted and interpreted at each stage. Here some extra costs may be incurred in construction of observation wells and maintenance of a monitoring program.

Near the Fall Zone, where the Coastal Plain sediments lap up against the inland consolidated rocks, only small supplies are available. Most wells there will not yield more than a few hundred gallons a minute.

COSTS

The following tables (1–4) show estimates of cost for wells ranging in yields from 150 gpm (a little less than 0.25 mgd) to 1,400 gpm (2 mgd). Well fields consist of wells arranged linearly 1,000 feet apart. These data are also plotted as shown by figure 5. Other well-field designs may be as economic or even more so, depending on many factors to be determined after site studies have been made. The data can be used only as a general guide to approximate costs if wells of stated yields can be developed and are

TABLE 1.—*Wells in Coastal Plain deposits: capital costs*

Yield (gpm)	Production well[a]	Screen	Develop	Pump	Test run	House and lot	Sub-total	Eng. & cont.	Total capital cost 1968	Total capital cost 1970
150	$5,100 300' x 6"	$350 5' x 6"	$400 2 days	$2,100	$480 24 hrs	$2,500	$10,930	$2,732	$13,662	$15,028
350	$7,500 375' x 8" 125' x 10"	$875 13' x 8"	$400 2 days	$3,400	$480 24 hrs	$2,500	$15,155	$3,788	$18,943	$20,837
700	$12,800 475' x 10" 125' x 14"	$1,495 21' x 10"	$600 3 days	$5,040	$960 48 hrs	$2,500	$23,395	$5,849	$29,244	$32,168
1,400	$25,100 575' x 12" 125' x 20"	$2,795 42' x 10"	$1,200 4 days	$8,800	$960 48 hrs	$2,500	$41,255	$10,264	$51,519	$56,670

a/ One unsuccessful well for each production well at 150 gpm only.

TABLE 2.—*Wells in Coastal Plain deposits: amortization and operational costs and unit costs of water*

Yield (gpm)	[a]Capital costs	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Cost per 1,000 gal. Equip. & maint.	Cost per 1,000 gal. Power	Cost per 1,000 gal. Total
150	$15,028	$1,082	$150	$1,232	$3.37	130	$.0259	$.009	$.035
350	$20,837	$1,503	$208	$1,711	$4.68	300	$.0156	$.009	$.025
700	$32,168	$2,316	$322	$2,638	$7.23	600	$.0123	$.009	$.021
1,400	$56,670	$4,082	$567	$4,649	$12.74	1,200	$.0106	$.009	$.020

TABLE 3.—*Wells in Coastal Plain deposits: cost of connecting pipe and total cost of water in multiple-well systems*

No. of wells	System capacity (mgd)	Capital cost (pipe)	Easements	Capital cost (total)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Added pipe cost	Total cost (1,000 gal.)
Wells yield 150 gpm											
1	.216	--	--	--	--	--	--	--	--	--	$.035
2	.432	$ 4,470	$ 47	$ 4,517	$ 325.2	$ 11.8	$ 336	$ .92	260	$.0035	.038
5	1.08	21,660	189	21,849	1,573	54.2	1,627	4.45	650	.0069	.042
10	2.16	63,490	426	63,916	4,602	159	4,761	13.04	1,300	.0101	.045
20	4.32	172,235	899	173,134	12,466	431	12,897	35.33	2,600	.0136	.049
50	10.8	635,646	2,318	637,964	45,933	1,589	47,522	130.19	6,500	.0200	.055
100	21.6	1,683,750	4,683	1,688,433	121,567	2,959	124,526	341.16	13,000	.0263	.061
Wells yield 350 gpm											
1	0.5	--	--	--	--	--	--	--	300	--	.0246
2	1.0	9,323	95	9,418	678	23	701	1.92	600	.003	.028
3	1.5	20,615	189	20,804	1,498	52	1,550	4.24	900	.005	.029
4	2.0	33,995	284	34,279	2,468	85	2,553	6.99	1,200	.005	.030
5	2.5	54,424	378	54,802	3,946	136	4,082	11.18	1,500	.008	.032
10	5.0	165,451	851	166,302	11,974	414	12,388	33.93	3,000	.011	.036
20	10.0	473,813	1,797	475,610	34,244	1,185	35,429	97.06	6,000	.016	.041
40	20.0	1,276,824	3,689	1,280,513	92,197	3,192	95,389	261.30	12,000	.022	.046
65	32.5	2,578,870	6,000	2,584,870	186,111	6,447	192,558	527.55	19,500	.027	.052
80	40.0	3,879,610	7,481	3,887,091	279,871	9,699	289,570	793.34	24,000	.033	.058

Wells yield 700 gpm											
1	1	--	--	--	--	--	--	--	600	--	$.0213
2	2	$ 10,307	$ 95	$ 10,402	$ 749	$ 26	$ 775	$ 2.12	1,200	$.0018	.023
3	3	27,212	189	27,401	1,973	68	2,041	5.59	1,800	.0031	.024
4	4	47,600	284	47,884	3,447	119	3,566	9.76	2,400	.0041	.025
5	5	70,530	473	71,003	5,112	176	5,288	14.49	3,000	.0048	.026
10	10	215,460	851	216,311	15,574	539	16,113	44.14	6,000	.0074	.029
20	20	621,110	1,797	622,907	44,849	1,553	46,402	127.13	12,000	.0106	.032
33	33	1,289,568	3,027	1,292,595	93,067	3,224	96,291	267	19,800	.014	.035
40	40	1,932,091	3,689	1,935,780	138,579	4,830	143,409	393	24,000	.016	.037
Wells yield 1,400 gpm											
1	2	--	--	--	--	--	--	--	1,200	--	.0196
2	4	13,606	95	13,701	986	34	1,020	2.79	2,400	.00116	.0207
3	6	35,272	189	35,461	2,553	88	2,641	7.23	3,600	.00201	.0216
4	8	61,965	284	62,249	4,482	155	4,637	12.70	4,800	.00264	.0222
5	10	91,664	473	92,137	6,634	229	6,863	18.80	6,000	.00313	.0227
10	20	283,210	851	284,061	20,452	708	21,250	58.21	12,000	.00485	.024
16	32	585,200	1,419	586,619	42,236	1,463	43,699	119.72	19,200	.00624	.026
20	40	885,461	1,797	887,258	63,883	2,214	66,097	181.09	24,000	.00755	.027
25	50	1,389,850	2,270	1,392,120	100,233	3,475	103,708	284.13	30,000	.00947	.029

TABLE 4.—*Wells in Coastal Plain deposits: summary of capital costs in multiple-well system*

No. of wells	System capacity (mgd)	Daily discharge (mgd)	Cost of wells	Cost of pipeline	Total capital cost
		Wells yielding 150 gpm			
1	0.216	0.13	15,028	- -	15,028
2	0.432	0.26	30,056	4,517	34,573
5	1.08	0.65	75,140	21,849	96,989
10	2.16	1.3	150,280	63,916	214,196
20	4.32	2.6	300,560	173,134	473,694
50	10.8	6.5	751,400	637,964	1,389,364
100	21.6	13.0	1,502,800	1,688,433	3,191,233
		Wells yielding 350 gpm			
1	0.5	0.3	20,837	- -	20,837
2	1.0	0.6	41,674	9,418	51,092
3	1.5	0.9	62,511	20,804	83,315
4	2.0	1.2	83,348	34,279	117,627
5	2.5	1.5	104,185	54,802	158,987
10	5.0	3.0	208,370	166,302	374,672
20	10.0	6.0	416,740	475,610	892,350
40	20.0	12.0	833,480	1,280,513	2,113,993
65	32.5	19.5	1,354,405	2,584,870	3,939,275
80	40.0	24.0	1,666,960	3,887,091	5,554,405
		Wells yielding 700 gpm			
1	1	0.6	32,168	- -	32,168
2	2	1.2	64,336	10,402	74,738
3	3	1.8	96,504	27,401	123,905
4	4	2.4	128,672	47,884	176,556
5	5	3.0	160,840	71,003	231,843
10	10	6.0	321,680	216,311	537,991
20	20	12.0	643,360	622,907	1,266,267
33	33	19.8	1,061,544	1,292,595	2,354,139
40	40	24.0	1,286,720	1,935,780	3,222,500
		Wells yielding 1,400 gpm			
1	2	1.2	56,670	- -	56,670
2	4	2.4	113,340	13,701	127,041
3	6	3.6	180,010	35,461	215,471
4	8	4.8	226,680	62,249	288,929
5	10	6.0	283,354	92,137	375,491
10	20	12.0	566,700	284,061	850,761
16	32	19.2	906,720	586,619	1,493,339
20	40	24.0	1,113,340	887,258	2,000,598
25	50	30.0	1,416,750	1,392,120	2,808,870

constructed according to the pattern used and cost assumptions made. Most site studies will show approximately what yield will be obtained in an area, but other factors influencing actual costs will have to be determined by the developer and applied against the estimates given here.

THE CONSOLIDATED ROCKS

AVAILABLE SUPPLIES

The yield of wells in consolidated rock ranges from almost nothing to many hundreds of gallons a minute. Further, the "average yield" of wells in any one area, as commonly given in the literature, is no guide to what might be obtained because most existing wells were constructed to supply water for domestic use. The "average yield," as determined from a consideration of all well yields in an area, therefore represents something a little greater than the average need and is not a measure of the full potential of wells in the rock type being studied.

A detailed study was made of published records of municipal and industrial wells in the North Atlantic Region (Cederstrom, 1972) as a basis for determining the average yields used here, on the assumption that when these wells were drilled, an effort was made to obtain a maximum supply of water. About 1,500 of some 15,000 published well records were selected and used as the basis for arriving at the yield figures in this report. Most of these wells are 350 feet deep or deeper and utilize about 100 feet of drawdown. The manipulations of the data and other aspects of that study will not be dealt with here. The assumptions are that the depth and drawdown are as stated; that the average yields, as given in the table, refer to wells that are somewhat widely distributed (for example, three dry wells drilled within a few tens of feet of each other near a water tank are considered as one well); and that well locations are selected by a hydrologist.

The number of wells to be drilled before the "sample" is large enough to yield the average is problematical. Perhaps five should be sufficient where the first one or two wells do not approach the average given in table 5. With this possibility in mind, producing-well costs given in tables 6–9 include the cost of one unsuccessful test hole. Thus, where three wells of average yield are sought, costs include the drilling of a total of six holes.

THE CRYSTALLINE ROCKS

Crystalline rocks, largely granite, schist, and gneiss, underlie most of the Piedmont, the Blue Ridge, the New England Upland, and the Adirondack provinces. Yields from wells in these rocks are generally low. Where the rocks are greatly fractured, as along prominent faults, a few hundred gallons per minute per well may be obtained, but ordinarily the average yield of properly located wells, 350–450 feet deep, is 75–100 gpm. Wells in valleys, gen-

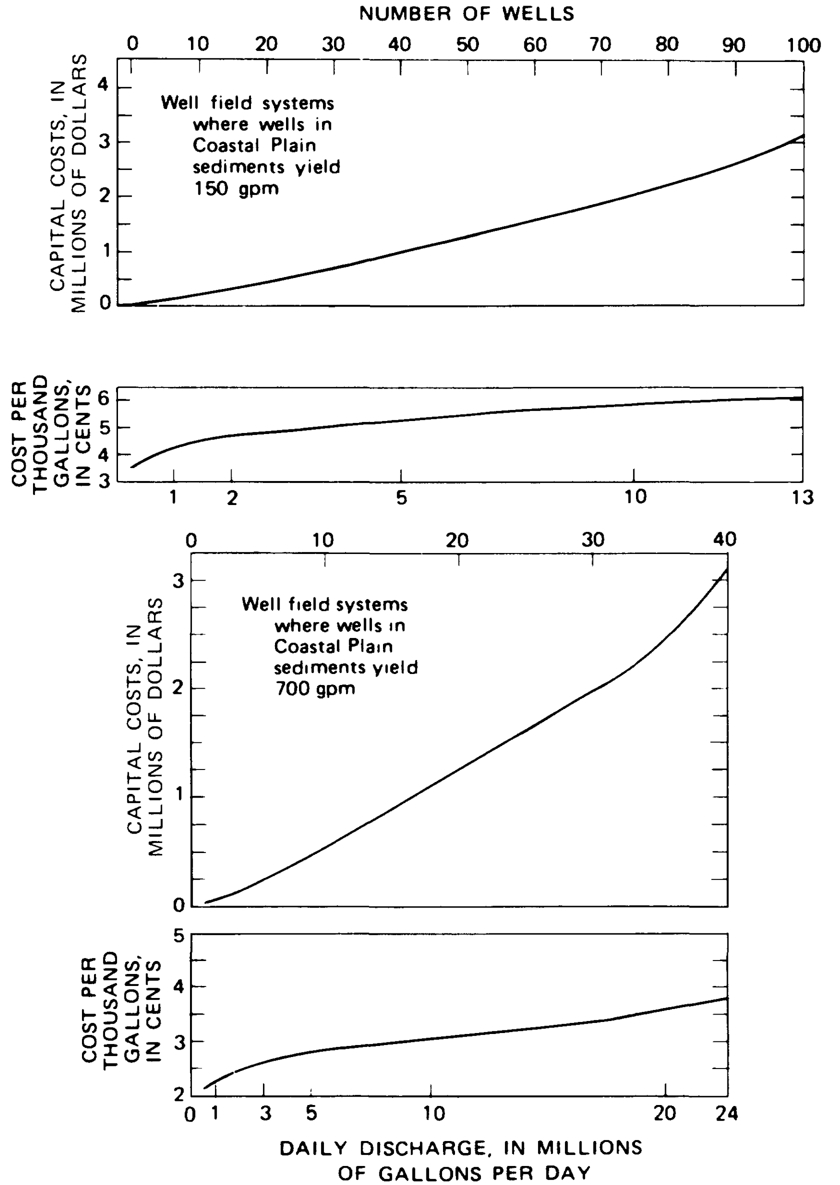

FIGURE 5.—Capital costs and cost per thousand gallons of water from wells in Coastal Plain sediments.

erally areas of more highly developed fractures, will ordinarily have the better yields, as will wells in areas overlain by thick saturated weathered rock or glacial sands. Prominent ridges commonly are underlain by solid rock masses and are poor locations

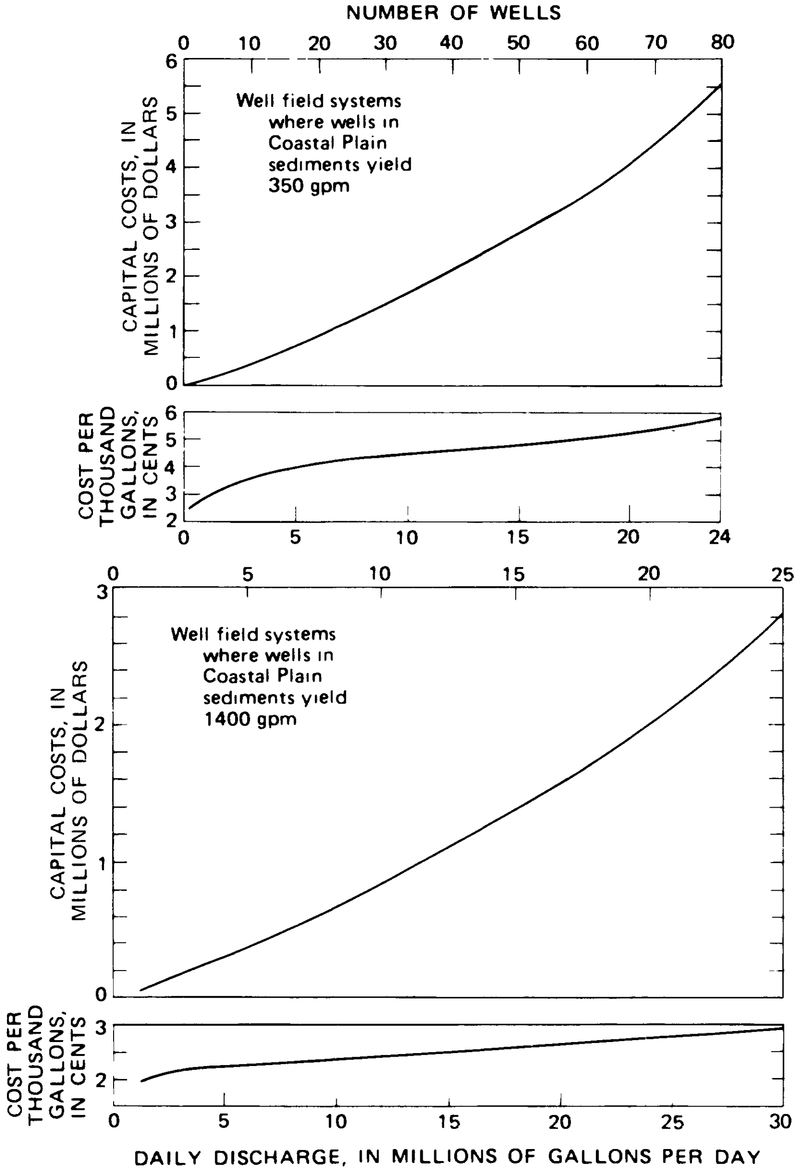

FIGURE 5.—Continued.

for wells. Yields of wells there may be only a few gallons a minute and the cost of water very high.

Marble is associated with other crystalline rocks in a few places. Wells in marble may have higher yields than those in the other crystalline rocks.

THE CONSOLIDATED SEDIMENTARY ROCKS

Consolidated sedimentary rocks—limestone and dolomite (carbonate rocks), sandstone, and shale—make up the Valley and Ridge and Appalachian Plateau provinces.

The carbonate rocks are commonly excellent water-bearing formations. The average yield of wells in multiple-well developments in the older massive limestones is about 300 gpm. However, some wells in limestone yield very little water and others are known to yield more than 1,000 gpm. Deep-well yields in sandstone of the Appalachian Valley generally average about 150 gpm in multiple-well developments.

Sandstone and associated rocks of Triassic age are present in central Connecticut and as a belt of variable width extending from southeastern New York into Virginia. Deep wells in the Triassic sandstones and associated conglomeratic rocks also have an average yield of about 150 gpm. The shales and volcanic rocks yield much less water.

Shale is a poor water-bearing formation. Wells in clay shale, such as is present in the Plateau province, probably have average yields of not more than about 40 gpm, but in the Valley and Ridge province, wells in the slaty or sandy shales may average about 75 gpm. Significant increments of water are generally not obtained below 250 feet in clay shales, but wells in sandy or slaty shales generally gain in yield down to a depth of about 400 feet or more.

The yield figures given in table 5 reflect what has been found in many places and what is a reasonable probability elsewhere. Where there are marked departures from general geological conditions, yields may be notably different from those given. For example, deep wells in the crystalline rocks of the Blue Ridge will undoubtedly have much poorer yields than wells in similar rocks in the Piedmont where the rocks are overlain by a thick blanket of saturated weathered material.

In applying the cost estimates given below, therefore, it is necessary to determine the rock type in order to have some idea of yields expected and, in turn, the other of magnitude of costs.

RECHARGE OF AQUIFERS

Many productive wells can be developed in the consolidated rocks of the North Atlantic Region. However, when the task of evaluating the cost of water in large quantity was undertaken, determination of the probable yield of multiple wells was only part of the answer to the problem. The other part of the problem was to determine how much water a unit area of ground will furnish under continuous pumping conditions.

TABLE 5.—*Estimated average yields of wells 350 to 450 feet deep in consolidated formations in multiple-well developments at 100 feet of drawdown*

Formation	*Yield (gpm)*
Limestone	300
Sandstone, northern New York[1]	100(?)
Sandstone, except northern New York	160
Shaly sandstone or sandy shale	100
Shale[2]	40
Slaty shale	75
Limy shale	75
Granite	90
Granite gneiss	50
Schist	90
Greenstone[1]	25(?)
Marble	100
Undifferentiated granite and metamorphic rocks, coastal New England and nonglaciated areas	90
Undifferentiated granite and metamorphic rocks, inland New England and New York[3]	50(?)

[1] Data are scanty.
[2] Wells in shale yield little or no additional water below a depth of about 250 feet.
[3] Yieds poor on up uplands but larger in alluviated valleys.

For broad planning purposes, it was assumed that recoverable recharge averages 0.5 mgd per square mile in areas underlain by limestone and sandstone south of the galciated area. It may be somewhat less where those rocks are overlain by glacial till. The recharge rate in the crystalline rock areas was also calculated on the basis of 0.5 mgd per square mile although recharge may exceed that figure slightly where those rocks are overlain by a thick weathered mantle and may be much less in northern areas of rugged topography where the rocks are overlain by glacial till. Shaly areas are considered to be recharged at an average rate of 0.25 mgd per square mile.

In the cost analyses given below, the recharge per square mile is taken into account with respect to spacing of wells and cost of pipeline in crystalline rocks, sandstone, limestone, and shale (fig. 6). It is assumed that wells operate only 60 percent of the time; thus, where wells yield 300 gpm, two wells in a 1-square-mile block would yield 0.86 mgd if operating full time, but would discharge only 0.52 mgd if operating 60 percent of the time.

In this report it is considered that in a limestone terrane, five wells will produce about 1.75 mgd from a catchment area of 3.5 square miles. However, at Elkton, Va., a plant manager stated that five wells there at 15-foot spacings yield a total of 8.5 mgd. Such very favorable situations are necessarily disregarded in the cost analyses given here.

As noted above, it is also assumed that there is no significant infiltration from streams, capture of extra runoff, or reduction of evapotranspiration, and that there is no reuse (recycling) of water pumped. These factors will be operative in many areas, and more water will be available and at less cost, particularly less pipeline cost, than is assumed in the calculations, but the determination of possible gains is difficult except in detailed site studies.

Theoretical well fields are laid out linearly, and possible gains from flow induced from outside each square mile are also not considered in the calculations. Thus, if a well field 1 mile wide extends 5 miles, according to the approach taken here, additional ground water could be obtained from another immediately adjacent well field 5 miles long and 1 mile wide without violating the assumptions for these calculations.

COSTS

Tables 6–9 show the estimated cost of water where well yields in consolidated rocks range from 75 to 300 gpm and where wells are spaced according to the patterns shown in figure 6. These data are also shown graphically as figure 7. As inferred, other arrangements are possible and may be preferable after conditions at any potential site are determined.

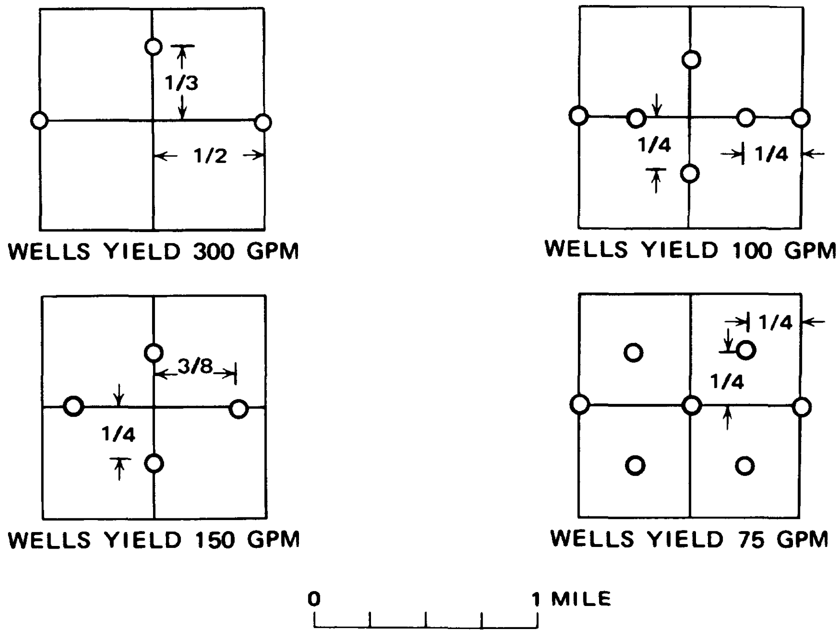

FIGURE 6.—Arrangement of wells and connecting pipe in consolidated rocks where average annual recharge is about 0.5 million gallons a day per square mile in each square mile shown.

TABLE 6.—*Wells in consolidated rocks: capital costs*

Yield (gpm)	Test well	Production well	Total drilling	Pump	Test run	House and lot	Sub-total	Eng. & cont.	Total capital cost 1968	Total capital cost 1970
75	($2,000)	($2,375) (125' x 8")	$4,375	$1,430	$360	$2,500	$8,665	$2,166	$10,831	$11,914
	(400' x 5")	(275' x 5")		75 gpm	24 hrs					
100	($2,000)	($2,375) (125' x 8")	$4,375	$1,700	$360	$2,500	$8,935	$2,233	$11,168	$12,285
	(400' x 5")	(275' x 5")		100 gpm	24 hrs					
150	($2,000)	($2,375) (125' x 8")	$4,375	$2,100	$360	$2,500	$9,335	$2,334	$11,669	$12,836
	(400' x 5")	(275' x 5")		150 gpm	24 hrs					
300	($2,000)	($2,375) (125' x 8")	$4,375	$3,500	$480	$2,500	$10,855	$2,714	$13,569	$14,926
	(400' x 5")	(275' x 5")		300 gpm	24 hrs					

TABLE 7.—*Wells in consolidated rocks: amortization and operational costs and unit costs of water*

Maximum yield (gpm)	Depth (feet)	Capital costs	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Cost per 1,000 gal. Equip. & maint.	Cost per 1,000 gal. Power	Cost per 1,000 gal. Total
75	400	$11,914	$ 858	$120	978	$2.67	64	$.0418	$.009	$.0498
100	400	12,285	885	123	1,008	2.75	87	.0316	.009	.0406
150	400	12,836	924	128	1,052	2.89	130	.0290	.009	.0303
300	400	14,926	1,075	150	1,225	3.37	260	.0129	.009	.0219

TABLE 8.—*Wells in consolidated rocks: costs of connecting pipe and total cost of water in multiple-well system*

No. of wells	System capacity (mgd)	Capital cost (pipe)	Easements	Capital cost (total)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Added pipe cost	Total cost (1,000 gal.)
Wells yield 75 gpm											
1	.108	--	--	--	--	--	--	--	64	--	$.0498
4	.43	$ 39,900	$ 500	$ 40,400	$ 2,909	$ 99.75	$ 3,009	$ 8.24	256	$.032	.082
6	.65	73,815	875	74,690	5,378	184.53	5,563	15.24	388	.039	.089
12	1.28	187,530	1,875	189,405	13,637	468.83	14,106	38.65	780	.050	.100
24	2.59	435,575	3,875	439,450	31,568	1,088.94	32,657	89.47	1,560	.057	.107
48	5.18	1,074,906	7,875	1,082,781	77,960	2,687.00	80,647	220.95	3,110	.071	.120
72	7.78	1,837,790	11,875	1,848,165	133,067	4,595.00	137,662	377.16	4,670	.081	.131
Wells yield 100 gpm											
1	0.144	--	--	--	--	--	--	--	86.4	--	.0406
5	.72	48,810	625	49,435	3,555	122	3,677	10.07	432	.023	.064
10	1.44	145,635	1,375	147,010	10,585	364	10,949	29.99	864	.035	.076
20	2.88	381,377	2,875	384,252	27,666	953	28,619	78.40	1,740	.045	.086
30	4.34	666,330	4,375	670,705	48,291	1,666	49,957	136.86	2,590	.053	.094
40	5.76	978,880	5,875	984,755	70,902	2,447	73,349	200.95	3,456	.058	.099
70	10.10	2,098,740	10,375	2,109,115	151,856	5,246	157,102	430.41	6,056	.071	.112

Wells yield 150 gpm											
1	.216	--	--	--	--	--	--	--	130	--	$.0303
2	.43	$ 17,689	$ 315	$ 18,004	$ 1,296	$ 44	$ 1,340	$ 3.67	260	$.014	.044
3	.64	38,570	435	39,005	2,808	96	2,904	7.95	390	.020	.050
4	.85	59,185	625	59,810	4,306	148	4,454	12.20	515	.024	.054
8	1.71	162,260	1,375	163,635	11,782	406	12,188	33.39	1,030	.032	.062
12	2.56	278,635	2,150	280,785	20,216	697	20,913	57.29	1,545	.037	.067
16	3.42	409,640	2,980	412,620	29,709	1,024	30,733	84.20	2,060	.041	.071
20	4.28	548,990	3,620	552,610	39,787	1,372	41,159	112.76	2,575	.044	.074
40	8.56	1,423,100	7,375	1,430,475	102,994	3,558	106,552	291.92	5,150	.056	.086
72	15.5	3,156,689	13,375	3,170,064	228,245	7,892	236,137	646.95	9,330	.069	.099
Wells yield 300 gpm											
1	.43	--	--	--	--	--	--	--	257	--	.0219
2	.86	39,408	417	39,825	2,867	99	2,966	8.16	515	.016	.038
4	1.7	125,246	1,084	126,330	9,096	313	9,409	25.77	1,030	.025	.047
6	2.6	246,715	1,750	248,465	17,889	617	18,506	50.70	1.543	.033	.055
12	5.1	543,970	3,750	796,185	57,325	1,337	58,622	160.50	3,090	.052	.074
36	15.4	3,029,740	11,500	3,041,240	218,969	7,574	226,543	622.50	9,261	.068	.090
60	25.7	6,089,405	19,750	6,109,155	439,859	15,220	455,079	1,250.00	15,400	.079	.101
80	34.4	8,928,300	25,925	8,954,225	644,700	22,320	667,020	1,830.00	20,640	.086	.108
100	42.3	10,391,000	38,100	13,858,100	997,783	25,977	1,025,760	2,805.00	25,750	.109	.131

TABLE 9.—*Wells in consolidated rocks: summary of capital costs of multiple-well systems*

Number of wells	System capacity (mgd)	Daily discharge (mgd)	Cost of wells	Cost of pipeline	Total capital costs
Wells yielding 75 gpm					
1	.11	.64	$11,914	---------	$11,914
4	.43	.26	47,656	$40,400	88,056
6	.65	.39	71,484	74,690	146,174
12	1.28	.77	142,968	189,405	332,373
24	2 59	1.56	285,936	439,450	725,386
48	5.18	3.11	571,872	1,082,781	1,654,653
72	7.78	4 67	857,808	1,848,165	2,705,973
Wells yielding 100 gpm					
1	0.144	0.086	$12,285	---------	$12,285
5	.72	.43	61,425	$49,435	110,860
10	1.44	.86	122,850	147,010	269,860
20	2 88	1.74	255,700	384,252	639,952
30	4.34	2.6	368,550	670,705	1,045,555
40	5.76	3.5	491,400	984,755	1,476,155
70	10.10	6.1	859,950	2,109,115	2,969,065
Wells yielding 150 gpm					
1	0.216	0.130	$12,836	---------	$12,836
2	.43	.26	25,672	$18,004	43,676
3	.64	.39	38,508	39.005	77,513
4	.86	.52	51,344	59,810	111,154
8	1.7	1.03	102,688	163,635	266.323
12	2.6	1.6	154,032	280,785	434,817
16	3.4	2.1	205,376	412,620	617,996
20	4.3	2.6	256,720	552,610	809,330
40	8.6	5.2	513,440	1,430,475	1,943,915
72	15.5	9.3	1,026,880	3,170,064	4,196,944
Wells yielding 300 gpm					
1	0.43	0.26	$14,926	---------	$14,926
2	.86	.52	29,852	$39,925	69,677
4	1.7	1.03	59,704	126,330	255,711
6	2.6	1.5	89,556	248,465	338,021
12	5.1	3.1	179,112	796,185	975,297
36	15.4	9 3	537,336	3,041,240	3,578,576
60	25.7	15.4	895,560	6,277,250	7,172,810
80	34.3	20.6	1,194,080	8,954,225	10,148,305
100	42.3	25.4	1,492,600	13,858,100	15,350,700

GLACIAL DEPOSITS

DISTRIBUTION

Glacial aquifers considered here are the stratified sands and gravels that are most widely distributed as valley fill adjacent to streams and rivers. Till, an ill-sorted mass of groundup rock, is not considered an aquifer in this report. Because the occurrence of sand and gravel deposits is highly irregular, the prediction of quantities of water available, and hence, the cost of producing water at any one locality, can only be arrived at after determination of conditions at the particular site. In the assessment made here, it is assumed that infiltration from an adjacent river or stream is sufficient to sustain the yield of wells in time of protracted drought with only small reliance upon water stored in the sediments or minimal local recharge from precipitation.

RECHARGE

As noted, it is likely that sustaining the higher yields will depend almost entirely upon induced filtration from an adjacent river or stream. Local recharge from precipitation on sandy glacial terrain averages as much as 1 mgd per square mile, and in such places, assuming that a reasonable amount of storage is present, water may be obtained without dependence upon induced infiltration from streams. However, geologic and hydrologic conditions vary greatly from one site to another and no attempt is made here to generalize on the cost of developing ground water where induced infiltration is not a prime factor. Because the storage potential of stratified glacial sediments is great, and recharge is relatively high, it is not implied that water in significant quantity may not be developed in many places where only local recharge is relied upon.

COSTS

Cost figures are based on various yields that may be obtained from wells, ranging from 100 to 1,400 gpm. Pipeline costs are based on a spacing between wells of 500 feet where wells yield 100 gpm and 1,000 feet where the wells have the higher yields shown.

In some areas, interference between high-yield wells which induce infiltration from a nearby river is so insignificant that wells may be spaced closer than 1,000 feet apart. In such areas, pipeline costs would be less than shown in the tables. In somewhat few places, yields of more than 2 mgd may be developed from a single well in glacial deposits.

Tables 10–14 show costs for water from wells in glacial sediments within the ranges that will commonly be developed for municipal and industrial supplies. It will be noted that for every production well, a test hole of 6- or 8-inch diameter is also budgeted. In some areas the test hole may be converted into a production well, thus lowering costs somewhat. In other areas, more than one test hole may be necessary.

Cost data are also shown graphically as figure 8.

At each of the stated yields, costs for wells 75 and 200 feet deep are given, thus encompassing the depths to which most wells will be drilled.

ECONOMY IN DEVELOPING GROUND-WATER SUPPLIES

CAPITAL EXPENDITURES

The greatest economies in developing ground water supplies may be gained by proceeding with well construction only after

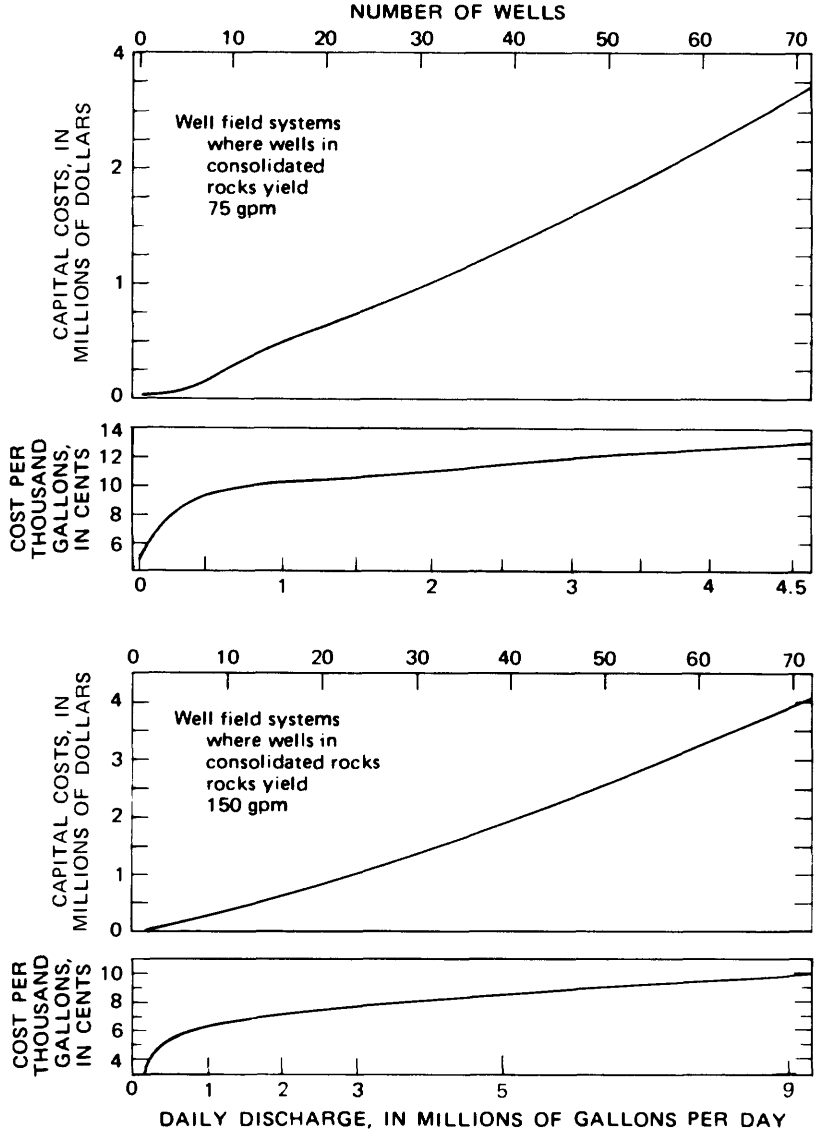

FIGURE 7.—Capital costs and cost per thousand gallons of water from wells in consolidated rocks.

maximum knowledge of the area and the aquifer to be developed is at hand and by constructing the type of well needed in the various environments that will be developed. The apparent savings effected by dispensing with the proper kind of professional advice, by failing to drill enough test holes, or by skimping on the construction of the well itself will commonly prove costly in the long run if not immediately.

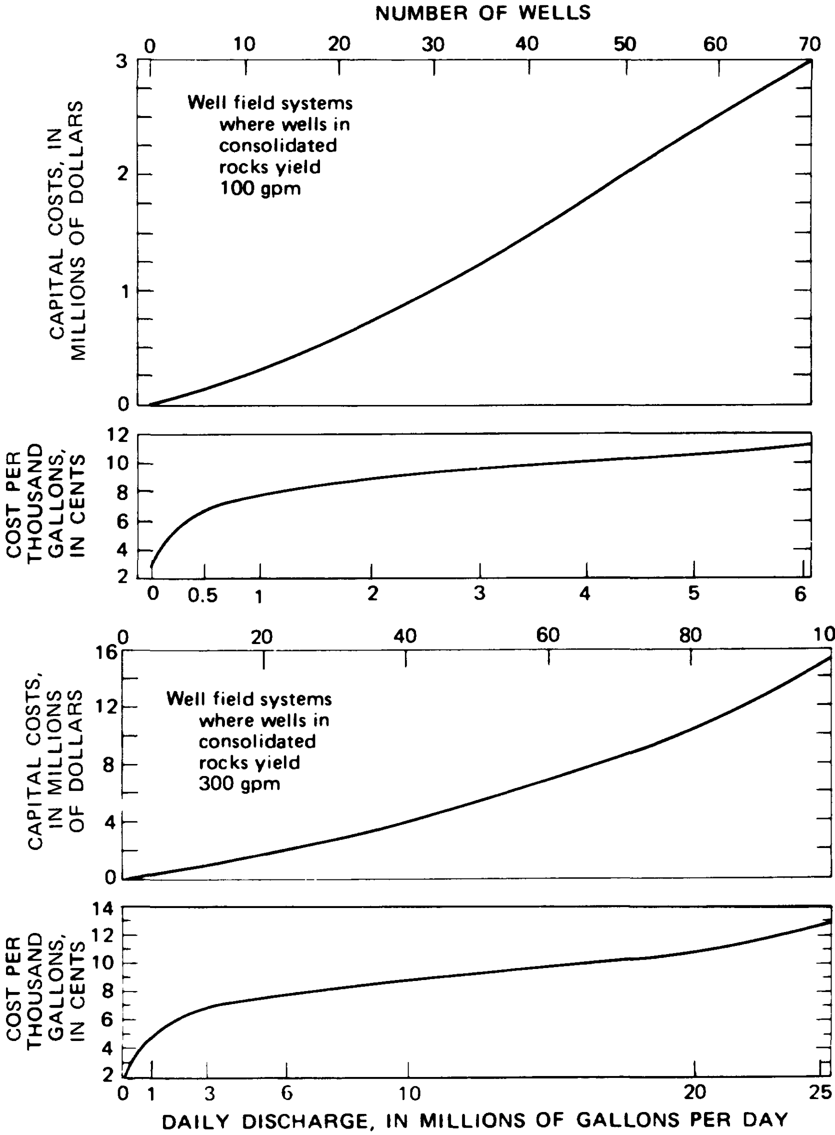

FIGURE 7.—Continued.

Ground water is very cheap where aquifer potential is commensurate with the demand imposed upon it. Small and, in some instances, large differences in capital costs become insignificant when cost per thousand gallons to the consumer is calculated. In the final analysis, it is that cost to the consumer which maintains the system and amortizes the initial costs of construction.

TABLE 10.—*Wells in glacial deposits: capital costs*

Maximum yield (gpm)	Test well or wells	Production well	Total drilling	Screen	Develop	Pump	Test run	House	Sub-total	Eng. & cont.	Total capital cost 1968	Total capital cost 1970
100 gpm	($525) (75')	($750) (75' x 6")	$1,275	$300 5' x 6"	$200 1 day	$1,700 100 gpm	$360 24 hrs	$2,500	$6,335	$1,584 25%	$7,919	$8,711
100 gpm	($1,400) (200')	($2,000) (200' x 6")	$3,400	" "	" "	" "	" "	"	$8,460	$2,115 "	$10,575	$11,636
350 gpm	($675) (75')	($1,050) (75' x 8")	$1,725	$715 10' x 8"	$400 2 days	$3,400 350 gpm	$480 24 hrs	$2,500	$9,220	$2,305 25%	$11,525	$12,678
350 gpm	($1,800) (200')	($2,800) (200' x 8")	$4,600	" "	" "	" "	" "	"	$12,095	$3,024 "	$15,119	$16,631
700 gpm	($1,350) (75')	($2,550) (75' x 14")	$3,900	$1,430 20' x 10"	$600 3 days	$5,040 700 gpm	$960 48 hrs	$2,500	$14,430	$3,607 25%	$18,037	$19,841
700 gpm	($3,600) (200')	($6,800) (200' x 14")	$10,400	" "	" "	" "	" "	"	$20,930	$5,235 "	$26,165	$28,782
1,400 gpm	($1,350) (75')	($6,800) (40' x 24", 30' x 18")	$8,150	$2,800 25' x 16"	$1,200 4 days	$8,800 14,000 gpm	$960 48 hrs	$2,500	$24,410	$6,103 25%	$30,513	$33,564
1,400 gpm	($3,600) (220')	($14,600) (40' x 24", 160' x 18")	$18,200	" "	" "	" "	" "	"	$34,460	$8,615 "	$43,075	$47,383

TABLE 11.—*Wells in glacial deposits: amortization and operational costs and unit cost of water*

Yield (gpm)	Depth (feet)	Capital costs (1970)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Cost per 1,000 gal.		
								Equip. & maint.	Power	Total
100	75	$ 8,711	$ 627	$ 87	$ 714	$ 1.95	86.4	$.0226	$.009	$.0316
100	200	11,636	838	116	954	2.61	86.4	.0302	.009	.0392
350	75	12,678	913	127	1,040	2.85	300	.0095	.009	.0185
350	200	16,631	1,197	166	1,368	3.73	300	.0124	.009	.0214
700	75	19,841	1,428	198	1,626	4.45	600	.0074	.009	.0164
700	200	28,872	2,079	289	2,368	6.49	600	.0108	.009	.0198
1,400	75	33,564	2,417	336	2,753	7.54	1,200	.0063	.009	.0153
1,400	200	47,383	3,412	474	3,886	10.65	1,200	.0089	.009	.0179

TABLE 12.—*Wells in glacial deposits: cost of connecting pipe and total cost of water in multiple-well systems where wells yield 100 gpm*

No. of wells	System capacity (mgd)	Capital cost (pipe)	Easements	Capital cost (total)	Annual amortiz.	Annual maint.	Annual cost	Daily cost	Daily discharge (1,000 gal.)	Added pipe cost	Total cost per 1,000 gal.	
											75 ft.	200 ft.
Wells yield 100 gpm												
1	0.14	--	--	--	--	--	--	--	86	--	$.032	$.039
2	0.29	$ 3,658	$ 47	$ 3,705	$ 267	$ 9.1	$ 276	$ .76	173	$.0044	.036	.044
3	0.43	8,313	95	8,408	605	21	626	1.72	259	.0066	.038	.046
4	0.58	13,606	142	13,748	990	34	1,024	2.81	346	.0081	.040	.047
5	0.72	18,886	189	19,075	1,373	47	1,420	3.89	432	.0090	.041	.048
10	1.44	52,136	426	52,562	3,784	95	3,879	10.62	864	.0122	.046	.051
20	2.88	148,295	899	149,194	10,742	370	11,112	30.44	1,728	.0176	.049	.057
40	5.76	392,350	1,845	394,195	28,382	980	29,372	80.47	3,460	.0232	.056	.063

TABLE 13.—*Wells in glacial deposits: costs of connecting pipe and total cost of water in multiple-well system where wells yield 350, 700, and 1,400 gpm*

Number of wells	System capacity (mgd)	Daily discharge (mgd)	Added pipe cost[1]	Total cost per 1,000 gal	
				75 ft	200 ft
Wells yielding 350 gpm					
1	0.5	0.3	-----	$0.019	$0.021
2	1.0	.6	$0.003	.022	.024
3	1.5	.9	.005	.024	.026
4	2.0	1.2	.005	.024	.026
5	2.5	1.5	.008	.027	.029
10	5.0	3.0	.011	.030	.032
20	10.0	6.0	.016	.035	.037
40	20.0	12.0	.022	.041	.043
65	32.5	19.5	.027	.046	.048
80	40.0	24.0	.033	.052	.054
Wells yielding 700 gpm					
1	1.0	0.6	-----	0.006	0.020
2	2.0	1.2	$0.002	.018	.022
3	3.0	1.8	.003	.019	.023
4	4.0	2.4	.004	.020	.024
5	5.0	3.0	.005	.021	.025
10	10.0	6.0	.007	.024	.027
20	22.0	12.0	.011	.027	.031
33	33.0	19.8	.014	.030	.034
40	40.0	24.0	.016	.032	.036
Wells yielding 1,400 gpm					
1	2.0	1.2	-----	0.015	0.018
2	4.0	2.4	$0 001	.016	.019
3	6.0	3.6	.002	.017	.020
4	8.0	4.8	.003	.018	.021
5	10.0	6.0	.003	.018	.021
10	20.0	12.0	.005	.020	.023
16	32.0	19.2	.006	.021	.024
20	40.0	24.0	.008	.023	.026

[1] Pipe cost data taken from table 3.

With reference to the first point mentioned, proper professional advice, the 15 percent budgeted in the tables for engineering, also provides for specialized hydrologic appraisals. It is firmly believed that expenditure of money thus budgeted will generally yield a "profit" or, at the very least, will insure that significant losses are not sustained.

Many well installations have been completed, some at quite reasonable cost, without the advice of professionals knowledgeable in the field of ground-water development. However, when overall results are assessed, it is quite clear that it is desirable and good economy to provide for professional advice before embarking on a well-drilling program, however small. From a cost point of view, the ideal well-development program will be based on the combined advice of a ground-water hydrologist or geologist, an engineer, and a knowledgeable member of the well-drilling profession.

TABLE 14.—*Wells in glacial deposits: summary of capital costs of multiple-well systems*

Number of wells	System capacity (mgd)	Daily discharge (mgd)	Cost of wells		Cost of pipeline[1]	Total capital costs	
			75 ft	200 ft		75 ft	200 ft
Wells yielding 100 gpm							
1	0.14	0.09	$8,711	$11,636	---------	$8,711	$11,636
2	.29	.17	17,422	23,272	$3,705	21,127	26,977
3	.43	.26	26,133	34,908	8,404	34,537	43,312
4	.58	.35	34,840	46,544	13,748	48,588	60,292
5	.72	.43	43,555	58,180	19,075	62,630	77,255
10	1.44	.86	87,110	116,360	52,562	139,672	168,922
20	2.88	1.73	174,220	232,720	149,194	323,414	381,914
40	5.76	3.46	348,400	465,440	394,195	742,595	859,635
Wells yielding 350 gpm							
1	0.5	0.3	$12,678	$16,631	---------	$12,678	$16,631
2	1.0	.6	25,356	33,262	$9,418	34,774	42,680
3	1.5	.9	38,034	49,893	20,804	58,838	70,697
4	2.0	1.2	50,172	66,524	34,279	84,991	100,803
5	2.5	1.5	63,390	83,155	54,802	118,192	137,957
10	5.0	3.0	126,780	166,310	166,302	293,082	332,612
20	10.0	6.0	253,560	332,620	475,610	729,170	808,230
40	20.0	12.0	507,120	665,240	1,280,513	1,787,633	1,945,753
65	32.5	19.5	824,070	1,081,015	2,584,870	3,408,940	3,665,885
80	40.0	24.0	1,014,240	1,330,480	3,987,091	4,901,331	5,217,571
Wells yielding 700 gpm							
1	1	0.6	$19,841	$28,782	---------	$19,841	$28,782
2	2	1.2	39,680	57,744	$10,402	50,082	68,176
3	3	1.8	59,520	86,346	27,401	86,921	113,747
4	4	2.4	79,360	115,128	47,884	127,190	163,012
5	5	3.0	99,205	143,910	71,003	170,208	214,913
10	10	6.0	198,410	287,820	216,311	414,721	504,131
20	20	12.0	396,800	577,440	622,907	1,019,707	1,200,347
33	33	19.8	654,753	949,806	1,292,595	1,947,348	2,242,401
40	40	24.0	793,600	1,115,128	1,935,780	2,729,380	3,050,908
Wells yielding 1,400 gpm							
1	2	1.2	$33.564	$47,383	---------	$33,564	$47,383
2	4	2.4	67,128	94,766	$13,701	80,829	108,467
3	6	3.6	100,692	142,149	35,461	136,153	177,610
4	8	4.8	134,256	189,532	62,249	196,505	251,781
5	10	6.0	167,820	236,915	92,137	259,957	329,052
10	20	12.0	335,640	473,830	284,061	619,701	757,891
16	32	19.2	537,024	758,128	586,619	1,123,643	1,344,747
20	40	24.0	671,280	947,660	887,258	1,558,538	1,834,918

[1] From table 3 for wells yielding 350, 700, 1,400 gpm.

Considering the water supply for a small municipality, assume that a well costs $12,800 (table 6) and yields 150 gpm. Water at the wellhead will be furnished at 3 cents a thousand gallons. If the 15-percent engineering cost were deducted, the cost to the consumer would be decreased less than two-tenths of a cent per thousand gallons. The saving can hardly appear great enough to warrant the risk of proceeding solely on the basis of general knowledge possessed by personnel who are not versed in various aspects of ground-water hydrology. Ground-water hydrology is not a simple discipline, and knowledge of the science (or prefer-

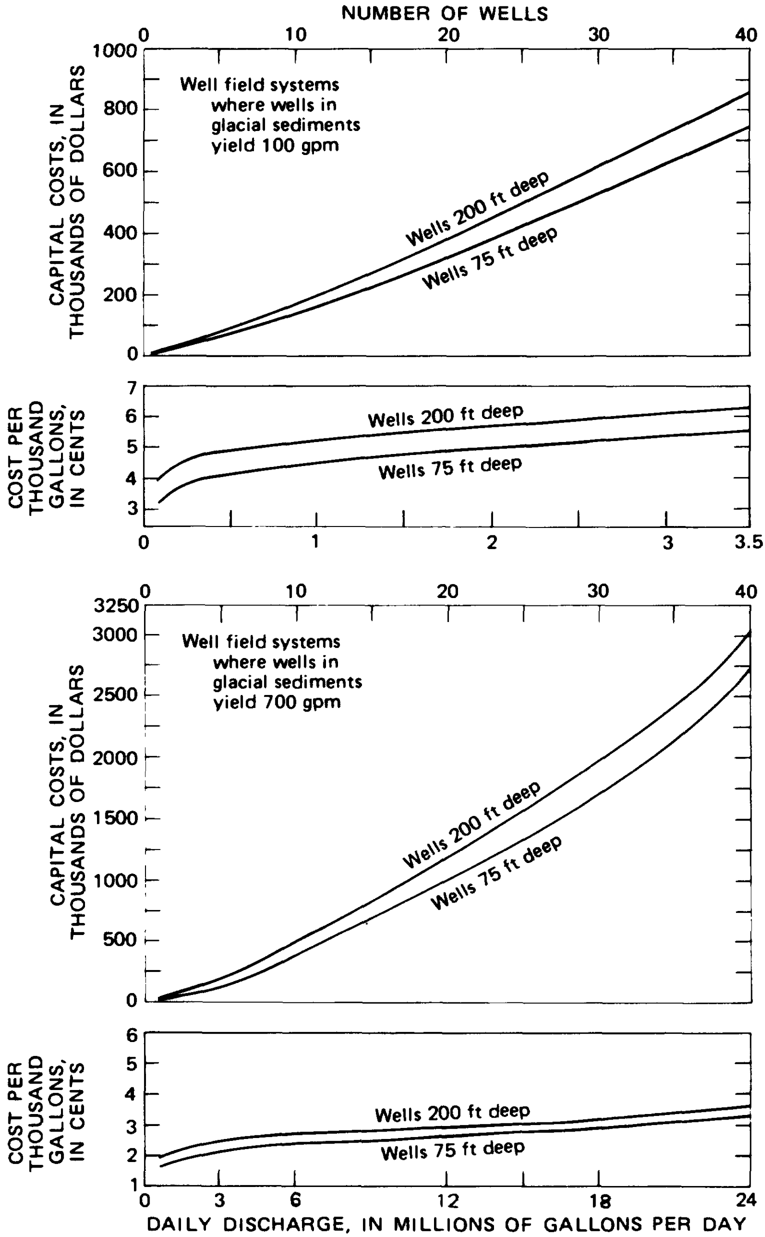

FIGURE 8.—Capital costs and cost per thousand gallons of water from wells in glacial sediments.

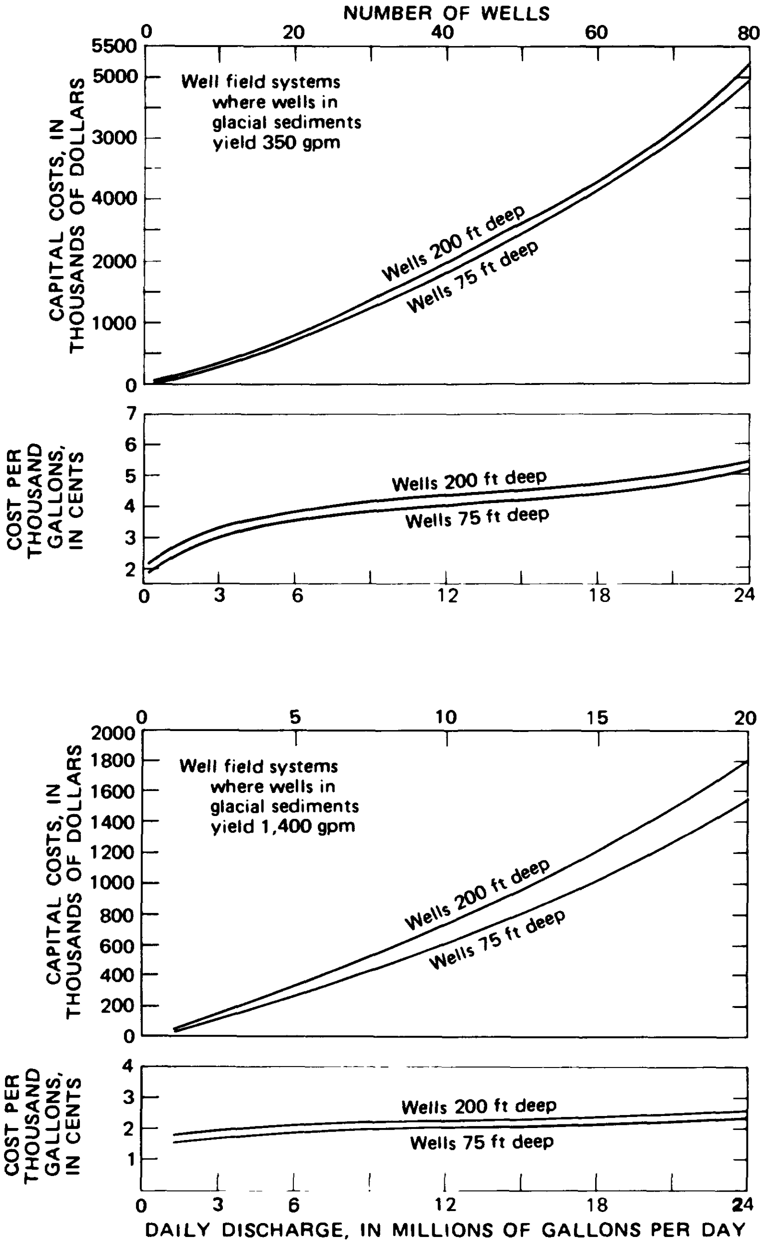

FIGURE 8.—Continued.

ably, the art) is no more well known to many technical people and some self-styled authorities than is the workings of a TV set to the average householder.

To save money by completing wells in granular sediments utilizing slotted pipe instead of screen, developing a well open-end, or failing to develop a well fully after screen is in place is literally asking for trouble and exepnse. If we consider a well in glacial sediments, 200 feet deep and yielding 700 gpm, water at the wellhead would cost about 2.0 cents per thousand gallons (table 11). Looking at the not insignificant item of a well screen, $1,970 budgeted ($1,430 for the screen and 25 percent for engineering and contingency plus 10 percent adjustment to the 1970 price level), how much might be saved by not using a screen? Only six-tenths of a cent per thousand gallons if the well produces 700 gpm 60 percent of the time. Although this is a 30 percent saving, it is not highly significant when actual dollar cost to the consumer is concerned. It would obviously be undesirable here to try to save the six-tenths of a cent in view of the very real probability of getting half or one-fourth the potential yield and an installation where water might cost almost 5 cents a thousand gallons instead of 2 cents and where the well might not be permanently stabilized.

The proper use of screens in wells in unconsolidated formations cannot be overemphasized. Directions on slot-size and length of screen to be used are commonly furnished by the manufacturer and are discussed in available handbooks. It is clear from the preceding calculation of cost aspects that in some wells the difference in capital costs, according to possible methods of finishing the well, is a relatively minor aspect of the problem. What is critical is the fact that proper design and small increased capital cost may easily result in 25 percent more available water. In some circumstances the extra water thus produced may eliminate the need for an additional well and connecting pipeline, with a saving of possibly many thousands of dollars.

TEST DRILLING

In the planning of a well field it seems clear from the preceding discussion that drilling of more than a minimum number of test holes may be quite rewarding in financial terms.

Looking at the cost elements of test holes relative to completed producing wells, it is seen that a 400-foot test hole in hard rock will cost about $2,700 (including engineering and contingency), whereas a 400-foot hole completed as a producing well, yielding 75 gpm, will cost about $9,200. Where the producing well yields 300 gpm, total costs would be about $12,100. The cost of a test hole, therefore, is fairly low relative to the cost of a completed well (Wyrick and Lloyd, 1968). Further, because the cost of test holes is a lesser factor in developing a well field, it may be worthwhile to abandon test wells that fail to yield the average volume exepcted in the formation being drilled.

We might compare results obtained by drilling a minimum number of holes in the Triassic sandstone and conglomeratic beds where an average yield of 150 gpm may be expected. If four holes were drilled and the average yield was 75 gpm, the cost of completing them as producers would be about $36,850 plus $39,900 for connecting pipeline, a total of $76,750.

On the other hand, if eight test holes were drilled and four of these attained an average yield of 150 gpm, the completed wells and test holes would cost $51,340 and connecting pipeline $59,180. Thus, for a total of $110,500, twice as much water would be produced as for $76,750. If it were necessary to drill 12 test holes to achieve the 150 gpm yields from four wells, the total cost would be about $123,300 as compared to $76,750 for completing the initial four low-yield wells as a source of supply. It would seem that making do with the results of initial test drilling would be a shortsighted economy where there is reason to expect that higher yields can be developed in the area.

Two cost factors come into play in these examples, both of which are to be compared to the relatively low cost of test drilling. One is the cost of finishing a test hole as a producing well. A pump in a well yielding 150 gpm will only cost about 20 percent more than the pump installed in a 75-gpm well, but the 150-gpm well yields twice as much water. In terms of cost per thousand gallons the difference is between, roughly, 5 cents a thousand gallons and 3 cents a thousand gallons. The gain of 2 cents per thousand is a 40 percent decrease in final costs.

The foregoing remarks point out the desirability of adequate test drilling. It should not be inferred from the discussion that indiscriminate drilling should be undertaken blindly in the hope of developing larger yield wells than those obtained in a minimum program. Rather, expansion of an initial program should be based on the following considerations:

1. The initial very few holes indicate that average yields for the rock type have not been developed.
2. Advice from professional hydrologists shows clearly or suggests that more likely locations have not been tested.
3. Pipeline costs to more likely locations would be less than the cost of developing lower yield wells closer to the point of use.

In any event, the moderate cost of test drilling, where a ground-water supply appears to be a logical answer to a need, may be considered as a simple insurance expenditure where an alternative supply would be very costly.

The yield of any one well in consolidated rock and, hence, the cost of producing water from any one well cannot be predicted. In the cost tables given it is assumed that it will be necessary to drill two test holes to locate one well that will have the average yield characteristic of municipal and industrial wells in that formation. Nevertheless, in developing a well field in consolidated rock, bad judgment or bad luck may prevail, and it may be desirable to drill more test holes to obtain adequate water. This may also be a problem where wells are to be developed in glacial deposits.

To show, in a different way, the relatively low cost of test drilling, let us assume that a small water supply is imperative in a particularly unfavorable crystalline rock area. Figure 9 shows the capital cost and cost per thousand gallons of water where 10 test holes were drilled and one or more of these are completed as production wells yielding 75 gpm.

The cost of a 400-foot test hole (table 6) is taken as $2,700 ($2,000 + 25 percent + 10 percent), and the cost of a completed well as $11,914 less $2,700, or about $9,200.

Where only one of the 10 test wells can be finished as a producing well with a yield of 75 gpm, the cost of water at the wellhead is about 11 cents per thousand gallons. Where two wells out of 10 are successful the cost per thousand gallons is about 7 cents a thousand, and so on.

Note that only small reductions in cost per thousand gallons are achieved as the degree of success rises from four successful wells out of 10 test holes to the point where all holes are capable of being completed as producers. This relationship shows rather clearly that only moderate success in test drilling is necessary to obtain a well-water supply at a rather reasonable cost, or conversely, the cost of drilling "extra" test holes is small where a moderate success is finally achieved.

It should be noted that each unsuccessful test hole drilled adds 8.2 mills ($0.0082) to the cost per thousand gallons to the water eventually produced from one 75-gpm well pumping 60 percent of the time. Costs would be somewhat less if test holes were abandoned as nonproductive at depths of 250–350 feet.

In most crystalline-rock areas it is unlikely that more than two or three wells would have to be drilled to develop 75 gpm if sites are chosen by a trained ground-water hydrologist. Most of the con-

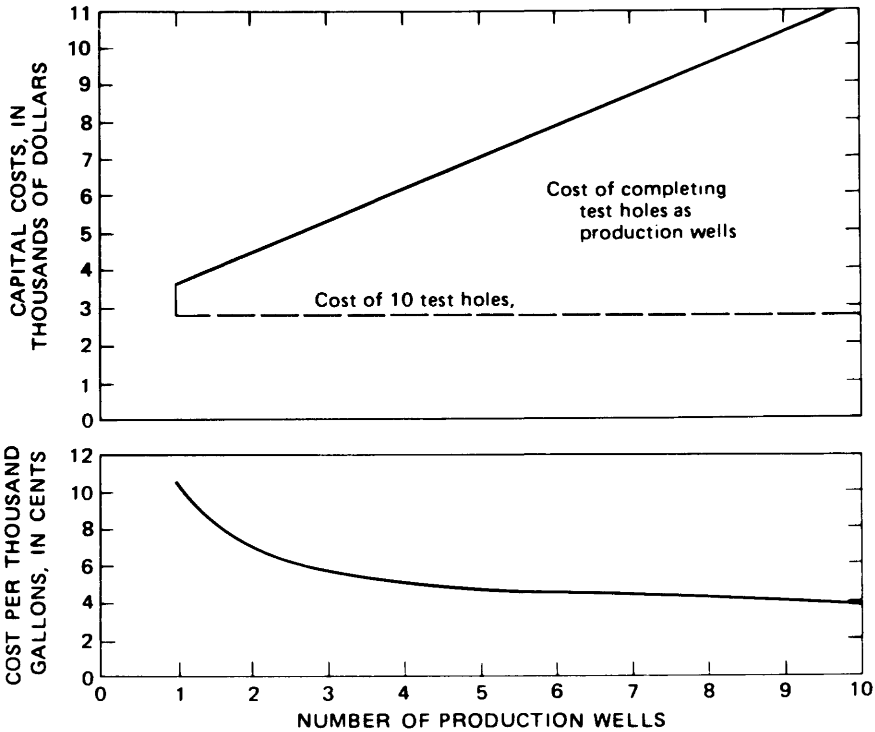

FIGURE 9.—Cost of water where one or more of 10 test holes are completed as producing wells, each yielding 75 gpm.

spicuous failures (low yields) in crystalline rock areas may be ascribed to the tendency to locate wells on massive-rock hilltops.

In exploring glacial deposits that may not be particularly favorable, the cost of each abandoned 75-foot test hole would add only 1.6 mills ($0.0016) per thousand gallons to the cost of water from the one well yielding 100 gpm.

Costs of pipeline have not been considered in the foregoing discussion.

TEST DRILLING BY JETTING METHOD

In some areas test holes are drilled in glacial sediments with a small-diameter jetting rig. This practice, in the writer's considered opinion, based on considerable field experience, is one of the most shortsighted "economies" that might be employed. The cost of such jet drilling was about $2.75 a foot, as opposed to a nominal cost of about $7.75 a foot for drilling a 6-inch-diameter hole where casing is recovered. If four locations were explored utilizing a 6-inch percussion drill to a depth of 100 feet, and one of the test holes could be converted into a producing well, the total cost might be $2,910 for the abandoned holes and $9,050 for the producing well, a total of $11,960. If on the other hand, four small-diameter holes were jetted and subsequently a 6-inch well was drilled at one of the sites, total costs would be $10,150, that is, the total job would have cost $1,810 less.

A "saving" of 15 percent of the capital cost in the example cited would seem to be a poor risk to take when failure might mean increasing the capital costs of obtaining a supply several times. Expressed in terms of cost per thousand gallons, where the producing well yields 100 gpm and operates 60 percent of the time, the "saving" becomes even less justifiable. The $1,810 saved—if drilling were successful using the jet drill—would lower the cost of water produced by lesst han 4 mills ($0.004) per thousand gallons. Going even farther, if the average water consumer uses 150 gallons per day, a family of three people would use about 13,000 gallons a month at an additional cost of 5 cents a month. Average household consumption per consumer is more likely about 55 gallons a day, in which case the extra cost would be less than 2 cents a month. The additional 2 cents or even 5 cents a month could hardly be thought of as an unreasonable price to pay for having a job done properly and avoiding the risk of a much more costly supply.

In drilling by the jetting method, there is no assurance whatever of being able to penetrate the full thickness of the glacial sediments. Tight fine sand, till, or boulders may pervent a wash or jet drill from attaining full penetration, hence, in many areas, desirable water-bearing formations at depth will not be located and a considerably more expensive supply might have to be developed. Shallow aquifers may not be present and, in any event, deeper aquifers will permit construction of wells having a greater available drawdown and greater storage potential.

In drilling in the glacial sediments in the Montpelier, Vt. area, it was found (Arthur L. Hodges, Jr., written commun., 1971) that the "wash drill" penetrated fine silty sand quite well but failed to reach bedrock in gravel or till. In one location wash-drill penetration failed at 63 feet, whereas cable-tool drilling established depth to bedrock at 87 feet. In a second location three wash-drill holes advanced to a depth of only 49 feet, but bedrock was reached by the cable tool at 100 feet. In both locations major aquifers were penetrated by the cable-tool drill below the total depth of penetration of the wash drill.

SPECIFICATIONS

From time to time it appears that detailed specifications for a production well are drafted before the aquifer characteristics are known. This practice will ordinarily not be in the best interests of the developer from a cost point of view. Even where development of water in a less complex rock environment is concerned, preliminary slim-hole drilling may indicate that certain straightforward preconceived measures should be eliminated or modified. In an environment of glacial or coastal plain granular sediments, much may be gained from a discussion of the test drilling results before the production well specifications are decided upon. The hydrologist, the engineer, or particularly the well-drilling representative may have suggestions to offer that will result in a lower cost per thousand gallons to the consumer. Specifically, the slot size and length of the well screen cannot be determined in advance of test drilling. The dimensions of the casing in the production well may be subject to decision after the fact of test drilling. The diameter of the upper part of a production well will be designed to accommodate a certain sized pump, and the lower part of the casing will permit installation of the appropriate screen. Gravel packing (actually, sand packing) may be desirable or even necessary where only fine sediments are present. Special conditions may call for departure from common practice.

Development time may be subject to modification as final stages of work on the production will proceed. This is of utmost importance in the somewhat shallow water-table wells in glacial deposits where available drawdown may be severely limited. If 3 days "extra" development at a cost of $200 a day were applied to a well producing initially 100 gpm, and if the yield of the well increased by 25 gpm as a result of the additional development, the extra 25 gpm would cost only about 3 mills per thousand gallons plus cost of lift, another fraction of a cent. Further, the additional 25 gpm might, in some circumstances, be sufficient to provide for the extra capacity required for peak loads, or, in multiple-well developments, four 125-gpm wells would provide as much water as five 100-gpm wells at a real savings in capital costs (including pipeline costs) as well as in cost per thousand gallons.

CONNECTING PIPE

Although the optimum pipe diameter to be chosen in any given situation is the task of the design engineer and will be predicated upon present and future needs of the consumer and on the geologic and hydrologic conditions of the area, the following remarks seem relevant in this paper.

Labor cost is the largest item in building pipeline. It would seem then that the additional cost incurred in laying line large enough to carry the full capacity of the wells rather than the minimum diameter required by present demand, would yield substantial gains in meeting peak demands, for fire protection, and in lower power costs. According to data given in figure 4, line carrying 70 gpm costs about $36,000 a mile installed, but a line carrying twice as much water will cost only $42,000. Pipe carrying 2 mgd (1400 gpm) costs about $72,000 a mile, whereas a pipe of twice that capacity will cost about $93,000 a mile. Regardless of price changes due to inflation or other factors, the relative costs will be much the same in the future. Thus, all pipeline connecting wells should be the recommended size for delivering the maximum yield of all wells operating simultaneously. Further, it will be good economics to anticipate future needs and provide for additional carrying capacity of the trunkline in the initial layout. In such well fields, hydrologic advice must be obtained to ascertain if additional supplies can be made available along the proposed trunkline at some future date.

Feeder lines from a trunkline to small-yield wells and the small-yield wells themselves are relatively expensive. Test drilling to locate higher than average yield wells and to eliminate lower yield wells wiill probably be good economics from the point of view of minimizing pipeline costs. To show pipeline costs in relation to yields of wells, we may consider a limestone area where 0.25-mile laterals are laid to two wells that yield 150 gpm each. Pipe would cost about $19,400 and the wells about $25,750, for a total of $45,150. If one 300-gpm well could be developed, costs would be 0.25 mile of lateral at about $11,870 and one well installation at $14,960, for a total of $26,830. The saving in capital cost of pipeline here is $7,530.

The difference in total cost here would be about $18,320, enough to pay for the drilling of about 2,700 feet of slim-hole exploration. That is, if initial drilling has developed a well with a 150 gpm yield, but there is a good change of developing a 300-gpm well, the cost of drilling the 150-gpm well may be charged off after which more than 2,300 feet of exploratory drilling may be justified in seeking to develop a 300-gpm well. Unfortunately, the yield of any one well in hard rock cannot be predicted, and, in the example given, success in locating the higher yield could not be guaranteed. However, in drilling five or six more test holes, even if a 300-gpm well could not be located, the probability is very high that two or more wells would have at least average yields of 150 gpm, and no real financial loss would be sustained.

For a small municipal development, it is estimated on the basis of assumptions used here that connecting pipe for a 1.28-mgd system delivering 0.77 mgd from wells producing 75 gpm each would cost $189,406, whereas in a well field where wells yield 300 gpm, the cost of pipeline required would only be about $75,000.

CONCLUSIONS

Ground water at the well head is relatively inexpensive. In multiple-well fields ground water is generally inexpensive where the capability of the aquifer is commensurate with the total demand. Owing to the cost of connecting pipe in multiple-well fields, production of more than 1 or 2 million gallons of ground water a day in some areas may be impractical, but in the more favorable aquifers development of several tens of millions of gallons a day may not be prohibitively expensive. Where large water requirements consist of many small to moderate demands at distinctly separate points, ground-water supplies may serve admirably from a cost point of view. Where a lesser but still large requirement must be satisfied at one point, development of ground water may not be practicable except as a supplementary or emergency supply.

Specialized knowledge judgment on the part of the ground-water hydrologist, the engineer, and the well driller are necessary in considering both the capabilities of the aquifer and the layout of the system. Only when these areas of competence are represented will the most practical and most economic supply be developed.

With reference to the writer's specialized field of competence, it is clear that the conclusions reached by a ground-water hydrologist after study of any plan for a ground-water supply are vital where real economies in developing a maximum supply of ground water are sought. The ground-water hydrologist will not only interpret the geological framework and the hydrologic principles involved in any area under consideration, but as exploration proceeds he will also weight costs of further test-hole drilling and chances of a greater success against final production-well and pipeline costs.

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