Specific Yield— Compilation of Specific Yields for Various Materials

By A. I. JOHNSON

HYDROLOGIC PROPERTIES OF EARTH MATERIALS

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By A. I. Johnson

ABSTRACT

Specific yield is defined as the ratio of (1) the volume of water that a saturated rock or soil will yield by gravity to (2) the total volume of the rock or soil. Specific yield is usually expressed as a percentage. The value is not definitive, because the quantity of water that will drain by gravity depends on variables such as duration of drainage, temperature, mineral composition of the water, and various physical characteristics of the rock or soil under consideration. Values of specific yield, nevertheless, offer a convenient means by which hydrologists can estimate the water-yielding capacities of earth materials and, as such, are very useful in hydrologic studies.

The present report consists mostly of direct or modified quotations from many selected reports that present and evaluate methods for determining specific yield, limitations of those methods, and results of the determinations made on a wide variety of rock and soil materials. Although no particular values are recommended in this report, a table summarizes values of specific yield, and their averages, determined for 10 rock textures. The following is an abstract of the table:

Specific yields, in percent, of various materials

[Rounded to nearest whole percent]

Material	*Number of determinations*	*Specific yield*		
		Maximum	*Minimum*	*Average*
Clay	15	5	0	2
Silt	16	19	3	8
Sandy clay	12	12	3	7
Fine sand	17	28	10	21
Medium sand	17	32	15	26
Coarse sand	17	35	20	27
Gravelly sand	15	35	20	25
Fine gravel	17	35	21	25
Medium gravel	14	26	13	23
Coarse gravel	14	26	12	22

INTRODUCTION

PURPOSE AND SCOPE

The purpose of this report is to assist hydrologists in estimating the quantity of water in storage in ground-water reservoirs by providing a compilation of specific yields representative of a variety of aquifer materials. The data presented here were compiled from published reports which have presented specific yields in relation to the texture of rock and soil materials. No attempt is made to evaluate the specific-yield data, but a table summarizes the published values for the convenience of the reader.

Not all specific yields from all published reports are listed in this report. However, this report does present a representative cross section of the publications noted as a result of rather lengthy library research. Along with pertinent tables or illustrations of data on specific yield, those parts of the text describing special methodology or the limitations of the data are quoted directly from each publication. Also presented are brief descriptions of all laboratory and field methods for determining specific yield and specific retention, to assist the reader in understanding the data compiled herein.

This report was prepared as a part of the specific-yield research studies made by the U.S. Geological Survey in cooperation with the California Department of Water Resources. The research testing was done at the Hydrologic Laboratory of the U.S. Geological Survey at Denver, Colo. The project was under the general supervision of Fred Kunkel, then district geologist of the Ground Water Branch of the Survey, Sacramento, Calif., and was under the direct supervision of A. I. Johnson, chief of the Hydrologic Laboratory.

DEFINITION OF TERMS

Most rock or soil materials contain interstices, or void spaces. The space commonly is described quantitatively by a property known as porosity. Porosity is defined by the American Society for Testing and Materials (1961) as the ratio, usually expressed as a percentage, of the volume of voids of a given soil mass to the total volume of the soil mass. For all practical purposes, ground water fills all void spaces in the saturated zone. From the previous definition, therefore, it follows that porosity is a measure of the quantity of water contained per unit volume (Todd, 1959).

Not all water contained in the saturated zone can be removed from the rock or soil by drainage or by pumping wells. Gravity ground water is that part of the water that will drain by gravity and thus be available to wells. That part of the water retained by molecular and surface tension forces in the void spaces of the rock and soil materials usually is known as retained water. The water-yielding capacity and water-retaining capacity of rock or soil materials are known as specific yield and specific retention. The specific yield plus the specific retention of a rock or soil is equal to the porosity of the rock or soil.

Meinzer (1923a, p. 28) defined the specific yield (ω_y) of a rock or soil, with respect to water, as the ratio of the volume of water that will drain by gravity from a saturated rock to the total volume of the rock, This ratio usually is expressed as a percentage.

Because specific yield represents the void space that will yield water to wells and is effective in furnishing water supplies, it is also known as effective porosity. However, because of the possible confusion with similar terms with slightly different meanings used by soil scientists (who also occasionally call it "noncapillary porosity") and by petroleum geologists, the term "specific yield" is preferred by the author and is used in this report exclusively.

The specific retention (ω_r) of a rock or soil, with respect to water, has been defined by Meinzer (1923a, p. 28) as the ratio that will be retained against gravity drainage from a saturated rock to the total volume of the rock. It usually is expressed as a percentage. Soil scientists and engineers use a similar measure called "water-holding capacity," but it is expressed as a percentage of the dry weight rather than of the volume. Water-holding capacity is defined (Am. Soc. Testing Materials, 1961, p. 1418) as "the smallest value to which the water content of a soil can be reduced by gravity drainage." The water-holding capacity can be converted to specific retention by multiplying by the dry unit weight of the rock or soil and then dividing by the unit weight of the water.

ACKNOWLEDGMENTS

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SOME FACTORS AFFECTING SPECIFIC YIELD

Meinzer (1923b, p. 52) indicated that the distinction between gravity water and retained water is not definitive, because the quantity of water that will drain from a rock or soil material depends on the length of time the rock or soil is allowed to drain, on the temperature and the mineral composition of the water—both of which affect its surface tension, viscosity, and specific gravity—and on various physical characteristics of the rock or soil under consideration. He noted (1923a, p. 29), for example, that a smaller proportion of water will drain from a short sample than from a long sample of the same material because a larger proportion of the short sample will remain sat-

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urated as part of the capillary fringe. Meinzer pointed out that methods for determining specific yield have been so little standardized that specific-yield data always should be accompanied by a statement indicating the methods used and, particularly, the size of sample and the period of draining under consideration.

The quantity of water yielded to wells from a body of saturated rock or soil thus depends upon the specific yield of the rock or soil and not upon its porosity. For example, the specific yield is 8 percent if a volume of saturated rock 10 feet thick and 100 feet square (100,000 cu ft) will supply 60,000 gallons (8,000 cu ft) of water when drained by pumping wells. If the rock still retains a total of 13,000 cubic feet of water in its void spaces after drainage, its specific retention would be 13 percent and its porosity would be 21 percent (8+13). Certain materials, such as clay, have high porosities and, thus, are capable of holding large quantities of water but yield only a small part of it under gravity drainage, even after a long period of time; consequently, these materials usually are worthless as aquifers.

The effect of duration of drainage upon specific yield has been noted by a number of hydrologists. Meinzer (1923b, p. 65) stated that most of the gravity water in a rock or soil material is yielded early in the drainage cycle but that there is apparently almost no limit to the duration that the slow draining will continue. He noted that fine-textured materials not only yield less water than coarse-textured materials but also yield it more slowly. He also indicated that, for most water-bearing materials, the volume of water drained by the rapid lowering of the water table in the immediate vicinity of a heavily pumped well is definitely much less than the total that would be yielded by long-term draining, but that the draining that accompanies the annual fluctuation of the water table is virtually complete.

Williams and Lohman (1949, p. 213, 220) stated that the true value of specific yield is obtained only after the saturated material has been drained for a long period of time. Using pumping-test methods in the field, the above authors concluded that their laboratory determination of about 25 percent specific yield were probably correct and that the apparent specific yield of 15 percent obtained near the beginning of the pumping period would have increased to about 19 percent by the end of the second year of pumping and probably would have reached the true value of 25 percent sometime during the third year of pumping. A report by Prill, Johnson, and Morris (1965, p. 51) presents quantitative information on the phenomenon of time-of-drainage effects on specific yield, as determined by laboratory drainage of long columns of material. These authors concluded that, even for sand-size materials, a period of 2 months to more than 1 year would be required for the drainage to reach equilibrium and, thus, give the maximum specific yield.

METHODS OF DETERMINING SPECIFIC YIELD

The specific yield of the rock or soil materials composing the zone of water-table fluctuation must be determined in order to estimate the available water supply represented by each increment of rise in the water table during a period of recharge. The specific yield is also needed to estimate the water supply obtainable from the materials for each increment that the water table is lowered. Although most field methods determine specific yield directly, most laboratory methods determine specific retention, and specific yield is found indirectly by subtracting the specific retention from the porosity.

Todd (1959, p. 24) stated that all methods have limitations—laboratory samples may be disturbed or may not be representative. The measurement and control of variables in field tests is difficult and many estimates lack accuracy.

Tolman (1937, p. 482) noted that "perhaps the greatest difficulty in the application of quantitative methods lies in the variability in the texture and hence in the hydrologic properties of the water-bearing materials. The hydrologic properties vary greatly, even with apparently slight differences in texture. Hence the ordinary geologic descriptions are quite inadequate for hydrologic purposes, and quantitative descriptions based on laboratory determinations have become essential."

During the past 6 or 7 decades, a number of laboratory and field methods have been developed for the determination of specific yield or specific retention. However, from the early 1900's until the writer started the specific-yield research project discussed in the report by Johnson, Morris, and Prill (1961), little work had been done by hydrologists in this country to determine specific yield by laboratory methods. To assist the reader in understanding the data compiled in this report, the various laboratory and field methods for determining specific yield are summarized briefly in the following paragraphs. (Also see Meinzer, 1923b, p. 53–76.)

LABORATORY METHODS

SAMPLE SATURATION AND DRAINAGE

The method of sample saturation and drainage consists of draining columns of saturated materials by gravity and determining both the volume of material drained and the volume of water yielded. The volume of water yielded can be measured directly or can be computed from the porosity and the moisture content after draining, but the columns must be long enough to avoid having an undue percentage of the column occupied by the capillary fringe. Meinzer (1932, p. 114) pointed out that care must be taken to prevent loss by evaporation and that the tests must be made at a uniform temperature or corrections for temperature variations must be applied. Because drainage continues for a long time at a diminishing rate, Meinzer also noted that the specific yield should be determined for specific periods of drainage.

As early as 1892 Hazen studied the water-retaining and water-yielding capacities of filter sands as related to their particle size. By alternately saturating and draining different-size sands, he found that the amount of water retained after the sand had drained increased as the particle size decreased. He found that the percentage of water retained by the fine materials was greater in the lower part of the bed than in the upper part. He explained this by stating that the height to which capillary attraction was effective was in inverse proportion to the square of the effective size of particles.

King (1899) published results of tests of the water-yielding and water-retaining capacities of five different sizes of sand. Five galvanized-iron cylinders 8 feet long and 5 inches in diameter were filled with sand, and water was introduced at the bottom of each cylinder until the sand was saturated. The columns were then allowed to drain for a period of 2½ years. Discharged water was measured or weighed at frequent intervals initially, and later only every few days, weeks, or months. At the conclusion of the tests, the quantity of water remaining in each 3-inch-thick layer of sand was determined. The results of King's tests showed discrepancies of about 5–7 percent between the porosity (representing the total water content possible under saturated conditions) and the total quantity of water accounted for. King's tests seemed to give lower values for specific retention than Hazen's tests, especially for the coarser samples.

Meinzer (1923b, p. 57) stated that the results obtained by Hazen and King are inadequate and cannot be used as a reliable basis for very definite conclusions as to water-yielding capacity. He concluded that many more tests of the same sort obviously were needed.

More recently, Johnson, Prill, and Morris (1963) made a detailed study of the column-drainage method and determined many of the factors affecting specific yield as determined by this method.

After a standard method was developed for packing columns of porous media (Morris and Kulp, 1961), the research determined that the column diameter (1- to 8-in.) made little difference in the moisture distribution after drainage, that the drainage characteristics made little difference when the media were cleaned with acid, and that similar results were obtained no matter what procedure was used for saturating the media. The distribution of moisture after drainage was similar when any one of four designs of column was used for the tests. Later research (Prill, Johnson, and Morris, 1965) studied the effect of time on column drainage and concluded that even for the sand-size materials used in the study, a very long time would be required to reach drainage equilibrium.

CORRELATION WITH PARTICLE SIZE

Particle-size analysis can be considered as one method of estimating specific yield. By determining the specific retention by some other method and the effective size, or median diameter, by particle-size analysis, the relation of the two can be graphically represented by a curve (Meinzer, 1923b, p. 64). By determining the effective size, or median diameter, of a sample and referring to the curve, the approximate specific retention can be obtained. After determining the porosity, the specific yield can then be obtained, as mentioned before. Probably, at best, this method represents a speedy but only approximate means for estimating specific yield.

Briggs and Shantz (1912, p. 72) determined the water-holding capacity by interpreting particle-size analyses and developed the following equation: Water-holding capacity = (0.03 sand + 0.35 silt + 1.65 clay) + 21, where the water-holding capacity and the sand, silt, and clay are expressed as percentages of the weight of the dry sample. Middleton (1920, p. 160) developed several similar equations which appeared to provide more precise relations than those of Briggs and Shantz.

As a part of the specific-yield-research study discussed earlier, Prill and Johnson (unpub. data, 1966) developed a relation between specific yield and soil texture for samples from the San Joaquin and Antelope Valleys, Calif. The data are shown by lines of equal specific yield on a trilinear graph of textural classification (fig. 1). The specific yields were determined by both laboratory and field methods, and the textural classes were determined by particle-size analysis of samples.

CENTRIFUGE-MOISTURE EQUIVALENT

Specific yield can also be estimated from the centrifuge-moisture equivalent. The latter is defined as the moisture content of a soil after it has been saturated with water and then subjected for 1 hour to a force equal to 1,000 times that of gravity (Am. Soc. Testing Materials, 1961, p. 1404). The centrifuge-moisture equivalent is multiplied by the dry unit weight of the soil and divided by the unit weight of water to obtain the moisture equivalent, expressed as a percentage of the volume.

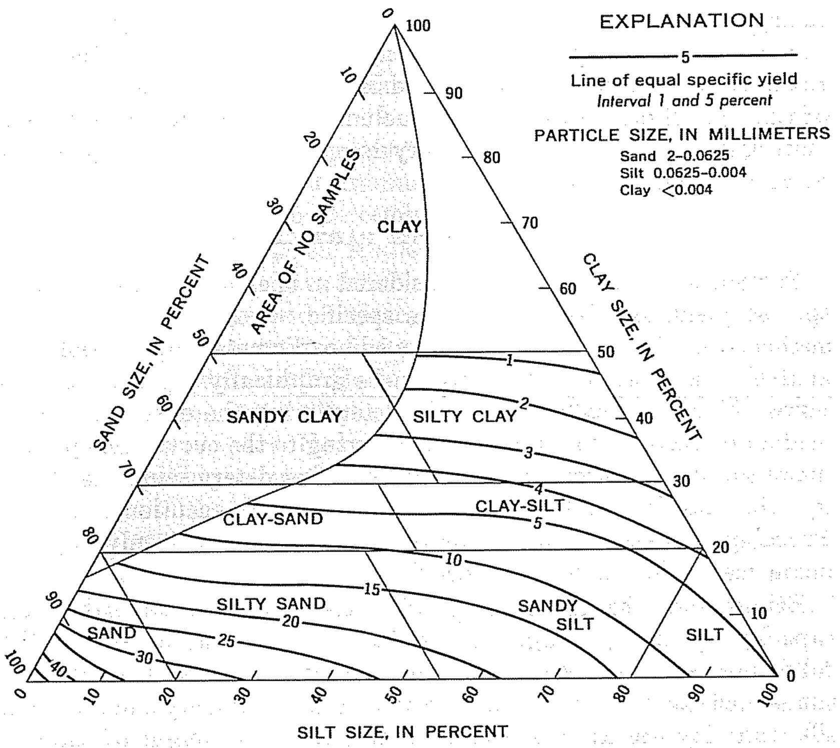

FIGURE 1.—Soil-classification triangle showing relation between particle size and specific yield.

The concept of moisture equivalent was introduced by Briggs and McLane (1907) by determinations made on more than 100 soils of the moisture retained under a centrifugal force 3,000 times the force of gravity. Stearns (1927) pointed out that the moisture-equivalent method is based on the theory of applying a centrifugal force great enough to reduce the capillary fringe enough that it can be ignored without introducing much error, even in small samples, and yet not so great as to withdraw a large proportion of the water that is held more securely above the capillary fringe. Stearns noted that if a material will lift water 100 inches by capillarity acting against gravity, the material will theoretically be able to hold the water only 0.1 inch against a centrifugal force that is 1,000 times greater than the force of gravity. Prill (1961) discussed this relation in more detail and pointed out that water retention after centrifuging is comparable to that obtained by gravity drainage of long columns.

Briggs and McLane (1907) made their early determinations under a centrifugal force of 3,000 times gravity, but in a later publication Briggs (1910) suggested that a force 1,000 times gravity could be used.

In 1912 Briggs and Shantz conducted moisture-equivalent tests employing a force 1,000 times gravity, and since then, that force has been accepted as standard by most investigators, including the U.S. Bureau of Public Roads (1942), American Society for Testing and Materials (1961), and American Association of State Highway Officials (1942). However, many studies have been made since 1912 concerning the relation of many other factors to the moisture equivalent obtained.

Considerable experimental work has indicated that for at least some medium-textured materials the moisture equivalent approximately equals specific retention. Israelson (1918) stated that correlations between the moisture equivalent and the water retention after irrigation closely correspond. In 1933 Piper determined a relation (fig. 2) between centrifuge-moisture equivalent and specific retention, as determined by the field drainage of long columns of various materials. Since that time, the centrifuge-moisture equivalent, as a percentage of the volume, has been adjusted to specific retention by multiplying by the ratio-correction factor determined by Piper (1933). This value is then subtracted from the porosity to obtain the specific yield.

In 1963 Johnson, Prill, and Morris reported a detailed study of the centrifuge-moisture-equivalent method. This research showed, for example, that the effect of temperature was of sufficient magnitude to warrant establishment of a standard temperature for the test (Prill and Johnson, 1959). Since 1959, centrifuge-moisture equivalents determined by the Hydrologic Laboratory have been made at a constant temperature of 20°C., and the American Society for Testing and Materials now (1966) has adopted this temperature as their standard for the test. (Prill and Johnson, 1966).

MOISTURE-TENSION TECHNIQUES

Moisture tension has been defined as the equivalent negative gage pressure, or suction, in the soil moisture. It is equal to the equivalent negative pressure to which water must be subjected to be in hydraulic equilibrium—through a porous permeable plate or membrane—with the water in the soil.

For tensions less than one atmosphere, the moisture-tension relations are determined by porous-plate apparatus consisting of a light-duty pressure chamber in which porous ceramic plates are installed. An air compressor maintains the air within the pressure chamber at a value equivalent to a given tension force.

Duplicate samples of the soil, retained in ½-inch-high plastic rings, are placed on the porous plates in the pressure chamber and are al-

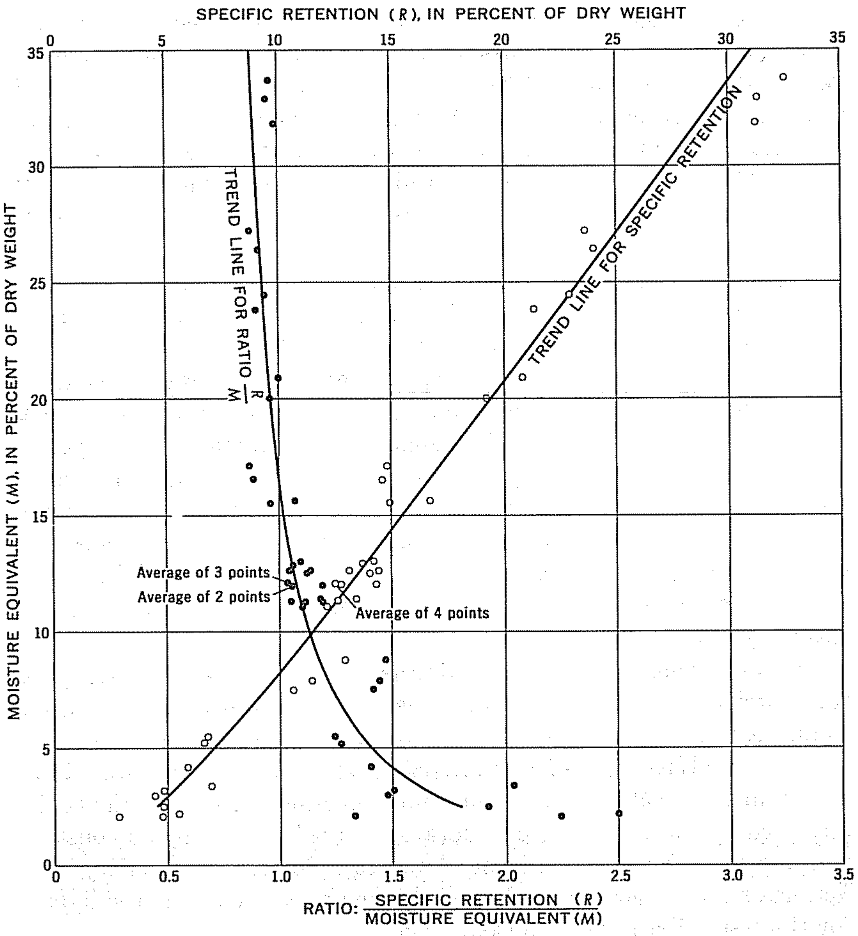

FIGURE 2.—Relation of moisture equivalent to specific retention. (After Piper, 1933.)

lowed to saturate by capillary action. The samples are subjected to a pressure equivalent to the desired tension until the water outflow from the pressure chamber has attained equilibrium. The samples are then removed from the pressure chamber, and the moisture content, by weight, is determined.

The moisture content at 1/10- to 1/3-atmosphere tension has been considered as approximately equivalent to the field capacity (Coleman, 1947; Richards and Weaver, 1944), which if converted to moisture content by volume, would approximate specific retention. Prill and Johnson (1967) investigated moisture-tension techniques in detail in the interest of applying these techniques to the routine determination of specfic retention. They found, for example, that the

moisture distribution in porous media as determined by moisture-tension techniques was comparable to that determined by gravity drainage of long columns.

Petroleum-reservoir engineers have used a mercury-injection method (Purcell, 1949) to determine the variation of capillary pressures (somewhat similar to moisture tensions) above the water table. The Hydrologic Laboratory currently is studying the adaptability of this method to the estimation of specific retention and specific yield.

FIELD METHODS

FIELD SATURATION AND DRAINAGE

The field saturation and drainage method is similar in principle to the laboratory method. Meinzer (1932, p. 115) indicated that a plot of land should be selected where the water table and capillary fringe are at sufficient depth below the surface to permit gravity drainage. The material underlying the plot should then be thoroughly wetted and allowed to drain, and care should be taken to avoid all possible evaporation. After a sufficient period of drainage, samples are taken for determination of moisture content and porosity, and the specific yield is computed as the difference between these two.

Israelson (1918) conducted a series of field tests of the water-retaining capacities of different-type soils in Sacramento Valley, Calif. His method was to determine the porosity of the different soils and their water content at successive depths immediately before irrigation and again about 4 days after irrigation. This second determination gave the approximate specific retention to be expected in a limited drainage time.

SAMPLING AFTER LOWERING OF WATER TABLE

After appreciable lowering of the water table, samples are collected from the zone immediately above the capillary fringe. The moisture content and porosity of the samples are determined, and the specific retention and specific yield are calculated. Meinzer (1932, p. 116) cautioned that, when making tests of this kind, it is essential to ascertain that the part of the deposit from which the sample is taken has not received any recent contribution of water from rain or irrigation, or that it has not been exposed to evaporation or to absorption by plants—both of which consume water that is retained against gravity by molecular attraction.

Experiments were made by Lee (Ellis and Lee, 1919) on samples of fill from the major stream valleys of San Diego County, Calif. His method was to collect samples immediately above the capillary fringe after the water table had been appreciably lowered, as commonly hap-

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pens in summer and autumn. Johnson and Kunkel (1963) discussed the results of this method in conjunction with moisture-content determination by nuclear meter, to determine the specific yield in the area of water-table lowering in the immediate vicinity of a large well field near Fresno, Calif. They found that the moisture distribution determined by this field method could be closely reproduced by data obtained by the centrifuge, moisture-tension, and column-drainage techniques in the laboratory.

PUMPING METHOD

This method consists of lowering of the water table by pumping a measured volume of water and then determining the volume of sediments drained. The specific yield is then obtained as the ratio of the volume of water pumped to the volume of sediments drained (Meinzer, 1932).

Pumping water from a well lowers the piezometric surface around the well and creates a cone of depression. In a carefully controlled pumping test, data are obtained on rate of discharge, water levels, and duration of pumping. The drawdown data are then used in various formulas to calculate the magnitude of one of the most important hydraulic characteristics of an aquifer—the coefficient of storage. Wenzel (1942, p. 87) defined the coefficient of storage as the cubic feet of water discharged from each vertical column of the aquifer with a base 1 foot square as the water level falls 1 foot. For water-table conditions, the coefficient of storage is equal to the specific yield of the material de-watered during the pumping. For artesian conditions the coefficient is equal to the water obtained from storage by compression of a column of water-bearing material whose height equals the thickness of the water-bearing material and whose base is 1 foot square.

Thiem (1906) apparently was the first hydrologist to develop a formula to determine aquifer characteristics by a well-pumping method. However, the greatest advance in aquifer analysis by well hydraulics was probably made through the development of the nonequilibrium formula by Theis (1935). The theory advanced by Theis introduced both the time factor and the coefficient of storage. Since 1935, many modifications of formulas or methods of interpretation have been developed.

Methods for computing storage coefficient (specific yield) by the pumping method were described in detail by Wenzel (1942), Ferris (1948), Brown (1953), Bruin and Hudson (1955), Remson and Lang (1955), Ramsahoye and Lang (1961), and Ferris, Knowles, Brown, and Stallman (1962). Most of the methods are based on the following assumptions: (a) The aquifer is homogenous and isotropic, (b) the aquifer has infinite areal extent, (c) the discharging well penetrates and receives water from the entire thickness of the aquifer, (d) the well diameter is infinitesimal, and (e) water removed from storage is discharged instantaneously with the decline of head. Although very few field conditions meet these specified limitations, successful application of the pumping method seems to be possible for many ground-water problems. Ferris (1948) pointed out that these methods can assist in the interpretation of local geology, but he also emphasized that any discrepancy between the hydraulic and geologic evidence in a given problem is untenable and points to incorrect interpretation of either or both sets of data.

Specific yield can also be estimated from moisture contents determined by sampling or by nuclear-meter logging in the cone of depression around a pumped well.

RECHARGE METHOD

The recharge method is the converse of the pumping method and consists of observing the seepage losses from streams or canals, or determining the amount of water recharged into an aquifer through a recharge well, and making corresponding observations on the resulting rise of the water table. From these observations, the volume of sediments saturated by the measured recharge is determined, and the specific yield can be computed (Meinzer, 1932, p. 116).

Moulder and Frazor (1957) used the recharge method to analyze aquifer characteristics near Amarillo, Tex., and found that water levels may have risen as much as 5 feet during a 4-month recharge period. Moulder noted that slow drainage or slow filling of sediments with water made the data collected early in the test unusable for analysis by the nonequilibrium method. He concluded that conformance to theoretical conditions requires longer periods of time at greater distances from the pumping or recharging well.

Sniegocki (1963) made a detailed study of the fundamental principles of artificially recharging aquifers through wells. Results of his study show that recharge data may be satisfactory for calculating absolute values for hydraulic characteristics, such as the specific yield (or coefficient of storage), for an aquifer. He concluded (Sniegocki, 1963, p. 22–23) that, if under certain conditions the field situation is readily adaptable for a recharge test, the testing period generally required to determine absolute hydraulic constants could be shortened as much as 90 percent. He noted that the coefficient of storage (specific yield) for the aquifer in his study was 0.30 (30 percent) after cyclical recharge for about 9 days; whereas, in the discharge situation, a value of 0.30 could not be obtained until pumping had continued for more than 100 days. Meinzer suggested earlier (1932, p. 136) that "better results can doubtless be obtained, however, if the specific-yield test is made during a period immediately after the well has been shut down, when the quantity of water taken into storage in the cylinder [cone of depression] will be equal to the total inflow during the period and the volume of material saturated can be computed from the rise of the water levels."

REVIEW OF LITERATURE

The following paragraphs present the results of library research to compile a list of specific yields for rock and soil materials of various textures. Pertinent parts of the publications describing the methods or limitations of the data have been quoted. All the following text is direct or only slightly modified quotation. Additions to quotations are indicated by brackets, and omissions are indicated by asterisks. Figure and table numbers, however, have been changed to fit their order of appearance in this report.

Clark, W. O., 1917, Ground water for irrigation in the Morgan Hill area, California, *in* Contributions to the hydrology of the United States, 1916: U.S. Geol. Survey Water-Supply Paper 400, p. 82–83.

The alluvium is composed, according to 69 well logs, of about 69 percent clay, 29 percent gravel, and 2 percent sand. From the available data on porosity * * * it has been concluded that the porosity of the sand and gravel is about 35 percent of its volume, that of the clay 32 percent, and that of the alluvium as a whole about 33 percent.

The vital question in this connection is not so much the total porosity of the materials and the total quantity of ground water present as the quantity of water that these materials will yield under a pump. Different materials by no means give up water to a pump in the proportion of the total water they contain. Fine materials are usually better sorted than coarser materials and therefore when saturated they may contain even more water than the coarser materials, but they permanently retain a large percentage of this water, whereas the coarser materials readily part with a large percentage of their water content. The fine materials are therefore of comparatively little value as water producers and the coarse materials are the important water-bearing formations.

The following table [table 1] shows the relative amount of water retained by sands of different degrees of fineness.

It will be seen from this table that the coarsest of the five sands tested gives up a quantity of water equal to 32.29 percent of the total volume of the sand, or somewhat more than 83 percent of the water it contains. The gravel and sand of the Morgan Hill district are on the whole considerably coarser than this sand and would give up a larger proportion of their water. For purposes of calculation it is assumed that they would give up about 90 percent of their total water content. If the alluvium includes 29 percent of gravel and 2

TABLE 1.—*Quantity of water retained and given up by different sands that were drained for 2½ years*

[Based on tables given by King (1899)]

Effective diameter of sand grains, in millimeters	Porosity of sands, expressed in percentage of total volume	Quantity of water retained, expressed in percentage of total volume of the sands	Quantity of water given up by the saturated sands, expressed in percentage of total volume of the sands
0.47	38.86	6.57	32.29
.18	40.07	7.37	33.70
.16	40.76	10.35	30.41
.12	40.57	12.49	28.08
.08	39.73	14.09	25.64

percent of sand, these materials will hold a quantity of water equal to 10.85 percent of the total volume of the saturated alluvium; if they will yeild 90 percent of this water they will furnish a quantity of water equal to 9.77 percent of the total volume of the saturated alluvium [table 2]. The clays form about 69 percent of the alluvium, and their average porosity is about 33 percent of their total volume. Clays give up a very small percentage of the water they contain. It is stated by King [1899] that clays of fine texture may retain as much as 32 percent of their dry weight of water.

TABLE 2.—*Specific yields for alluvial deposits in the Morgan Hill area, Santa Clara Valley, Calif.*

Material	*Specific yield (percent)*
Gravel, with sand	10
Clay loam	2

The materials called clay in the Morgan Hill area are not true clays but perhaps more nearly clay loam, so that the quantity of water they retained would be considerably less than that retained by fine clay. The porosity of fine clays would be greater, but the clays from which the porosity data here used were obtained were not true clays, and hence it is believed that their average porosity represents the porosity of the clays of the Morgan Hill area. It is thought that 90 percent of the amount required for saturation is a liberal estimate for the quantity of water retained by the clays of the Morgan Hill area—that is, they would give up 10 percent of the amount required to saturate them. As about 69 percent of the alluvium is clay and the porosity of this clay is taken as 33 percent of its volume, the pore space in the clay is equal to about 22.77 percent of the total volume of the alluvium. If it gives up 10 percent of the water required for saturation the clay would yield a quantity of water equal to 2.28 percent of the volume of the saturated alluvium [table 2]. The total water that the saturated alluvium will give up is therefore calculated to be 12.06 percent of its volume.

Ellis, A. J., and Lee, C. H., 1919, Geology and ground waters of the western part of San Diego County, California: U.S. Geol. Survey Water-Supply Paper 446, p. 121–123.

Experiments made by the writer on 36 samples from the fill of the major river valleys of San Diego County, the material varying from coarse sand to silt, indicated total voids expressed as percent by volume as follows: Coarse sand, 39 to 41 percent; medium sand, 41 to 48 percent; fine sand, 44 to 49 percent; fine sandy loam, 50 to 54 percent. The average porosity of all 36 samples was 45.1 percent. The classification of materials is that used by the Bureau of Soils of the United States Department of Agriculture. These percentages represent the porosity of the material under natural condition as to size and arrangement of grains [table 3].

* * * * * * *

TABLE 3.—*Specific yields of valley-fill materials in San Diego County, Calif.*

Material	*Specific yield (percent)*
Coarse sand	34
Medium sand	37
Fine sand	37
Fine sandy loam	30

A certain proportion of the moisture that occupies the voids of any saturated porous material does not readily drain out, even when the zone of saturation has fallen below the depth from which the capillary rise of water is rapid. This moisture can not be extracted by pumping nor does it represent water that drains out and is replenished during the natural fall and rise of the water table. To determine the water-retaining capacity of various valley-fill materials, six experiments were made after the annual summer lowering of the water table had taken place. The water-retaining capacity was found to range from 6 to 10 percent in the coarse, medium, and fine sands, but no finer materials were examined where the depth to the water table was great enough to enable the field capacity to be determined with certainty. Etcheverry [1915], quoting from Widtsoe's extensive experiments, gives the water-retaining capacity of sandy loam as 14½ percent by weight, which is equal to about 22 percent by volume, and this percentage can be considered as representing roughly the condition in sandy loam soils of the major river valleys under consideration. The total volume of water that might be drained from the valley fill by the slow lowering of the water table can be estimated as ranging from about 33 to 37 percent by volume. Such complete drainage, however, requires considerable time, and the relatively quick drainage resulting from the artificial lowering of the water table by pumping undoubtedly represents the extraction of far less of the total water content. In practice the proportionate volume that could be extracted from the valley fill of the major valleys probably does not exceed 20 to 25 percent. * * *.

Stearns, H. T., Robinson, T. W., and Taylor, G. H., 1930, Geology and water resources of the Mokelumne area, California: U.S. Geol. Survey Water-Supply Paper 619, p. 151–172.

Experimental field tests were made on undisturbed soil columns to determine the specific yield of the soil directly above the water table. These soil columns were obtained during the fall, when the water table was at its lowest level. In this way a test was made of the soil within the belt of fluctuation of the water table.

A cylinder 18 inches in diameter and 36 inches long made of 16-gage galvanized iron was used for the tests. The cylinder was butt-jointed and riveted, and the joints were floated with solder and scraped smooth on the inside. A 3-inch iron collar was riveted and spot welded to the top of the cylinder to prevent damage

to the cylinder in driving it. The bottom outside edge of the cylinder was beveled with a file to facilitate driving, and three equally spaced holes were drilled near the top, through which wires were placed to lift it.

A 4-foot square pit was dug within 3½ or 4 feet of the water table. The cylinder was then driven into the bottom of the pit, and the soil was excavated around the cylinder as driving progressed. A driving cap of 2-inch planking was used on top and a 4 by 4 inch timber about 14 feet long, handled by two men, was used in a manner similar to a pile driver. Constant care was taken to keep the cylinder in a vertical position while it was being driven. Special care was taken as the soil neared the top of the cylinder to keep the soil from being compacted by the driving cap. Driving was stopped when the bottom of the cylinder was within a few inches of the water table. A strong flexible wire was then used to saw through the soil column at the bottom edge. Heavy wires were strung through the holes near the top of the cylinder by means of which the cylinder was lifted a fraction of an inch by either a lever or block and tackle. The cylinder was suspended only long enough to allow a 24 by 24 inch 16-gage galvanized-iron base plate to be slipped under it. If the soil was not compact enough to remain in the cylinder when lifted this much, the plate was forced under the cylinder by means of an automobile jack, special care being used to keep the plate flush with the bottom edge of the cylinder. The latter method proved to be the simpler of the two. The cylinder was then centered on the plate and leveled. It was found that for the base plate 12-gage galvanized iron is preferable to 16-gage.

Two 1½-inch holes were then drilled in the confined soil column about 4 inches from diametrically opposite sides of the cylinder. These holes were drilled to the bottom of the soil column with a wood auger welded to an extension handle. They were then cased with 1½-inch nickel-plated brass pipes. One of the pipes was perforated the entire length, except 6 inches on the upper end, and the other pipe was perforated only in the lower 6 inches. The perforations were one-sixteenth of an inch in diameter and were drilled in parallel rows about half an inch center to center. * * *.

Water was added to the soil in the cylinder by pouring it into the 1½-inch hole in which only the lower 6 inches of the casing was perforated. The water was removed from the cylinder by drawing it up into a glass tube or rubber hose, and the amount of water removed or added was measured in a glass graduate.

The distance to the water level in the small holes was measured with a steel tape from the bottom edge of a spirit level placed across the top of the cylinder. A small lead weight, with a blunt point, was placed on the end of the tape, and the measurement was taken when the point of the weight broke the mirror surface of the water in the 1½-inch holes. Measurements were made in one hole immediately after measurements had been made in the other, to ascertain whether or not the water table in the cylinder was level.

* * * * * * *

* * * the resulting specific yield would have been larger and more nearly the actual specific yield if the time interval between changes of water in the cylinder had been greater. Experiments conducted the following year proved that an interval of several days is necessary to obtain accurate results.

Tests 1, 2, and 5 are completed, but the remainder of the tests are still in progress, and the data obtained will be given in a later report. Additional observations are necessary and may change the results given here, hence these data are of a preliminary nature and subject to revision [table 4].

TABLE 4.—*Specific yields of water-bearing materials in the Mokelumne area, near Lodi, Calif.*

Material	*Specific yield (percent)*
Medium sand	20
Silty sand	10
Sandy silt	2
Sandy clay	2
Clay	1

Test 1.—The time interval allowed for each determination was not long enough for accurate results. The average specific yield for a rising water table was 1.04 and for a falling water table 0.59. The average of the two is 0.82. The soil tested consisted of fine black clay and coarse black sand. The test was made chiefly on the fine black clay, which has a low specific yield and the result obtained is about what would be expected.

Test 2.—The soil was mainly a medium-coarse brown sand, hence the specific yield should be relatively high. The time interval for the first part of the experiment was short, being not over 45 minutes, but for the last part of the test the time interval ranged from about 1 hour to 50 hours. The specific yield was about 20.

Test 3.—The results of this test are not yet satisfactory, the specific yield ranging from 4.26 to 20.2. The soil is similar to that of test 2, and a specific yield of 15 or 20 would be expected. The temperature correction curves were not definite, but the corrections obtained were 0.015, 0.0084, and 0.014 foot per degree.

Test 4.—The soil tested was a very fine black sandy clay with a low specific yield. Owing to an undetected leak in the cylinder only one determination has been obtained so far. The specific yield was 4.4; corrected for temperature, 2.44. Two fairly well defined temperature correction curves have been obtained, showing corrections of 0.0096 and 0.0087 foot per degree.

Test 5.—The soil tested was a brown silty sand. This is doubtless the best test of the group and showed a specific yield of about 10. Very well defined temperature correction curves were obtained, giving corrections of 0.008, 0.0266, 0.0065, 0.0079 and 0.006 foot per degree. The time required for the water table to reach an equilibrium was established as being at least 25 days.

Test 6.—The soil tested was a fine black sandy silt. The specific yields were 1.6 and 1.4; corrected for temperature, 1.2 and 2.6. Fairly well defined temperature correction curves were obtained, showing corrections of 0.0264, 0.0112, and 0.0192 foot per degree. The time interval required for the water table to reach an equilibrium after a change of water was 43, 38, and 38 days for three series of observations.

Test 7.—The soil tested was a hard fine brown and gray sandy clay. Leakage caused considerable difficulty, and only one result of 13.6 for the specific yield was obtained. This result is believed to be high for soil of this texture, but additional data are needed to prove it. The result was obtained for a rising water table and would be too high if there was a small undetected leak in the cylinder. This is possible, for seven days after the last observation was made a leak appeared. Between February 5 and 16, 1929, a well-defined temperature correction curve was obtained, showing a correction of 0.055 foot per degree. Another series of observations gave no definite temperature correction curves, which may be an indication that an undetected leak was present.

Test 8.—The soil tested was a very hard sandy clay. The results are not consistent, for two tests gave a specific yield of 0.16 and 0.15 for a falling water table, and two tests gave 0.64 and 0.62 for a rising water table. Application of the temperature corrections to the results did not make them more consistent. The temperature correction curves were fairly well defined and showed corrections of 0.55, 0.033, 0.0218, 0.0168, 0.0172, and 0.018 foot per degree.

If there were no recharge from April to September, and no discharge other than that by pumping from wells during this period, and if all the pumping occurred during this period, the specific yield could be approximately computed by dividing the average volume of water withdrawn (53,800 acre-feet) by the average volume of material unwatered (360,200 acre-feet). Such a computation would give a specific yield of about 15. If allowances are made for the modifying factors, however, it appears that the specific yield is more nearly 10. Intensive investigation that is now in progress should give a more accurate figure for average specific yield. * * *.

White, W. N., 1932, A method of estimating ground-water supplies based on discharge by plants and evaporation from soil, in Contributions to the hydrology of the United States: U.S. Geol. Survey Water Supply Paper 659, p. 74–76.

Determinations of specific yield were first made with the disturbed soils with which the tanks were filled, and it seemed for a time as if the questionable figures thereby obtained were the best that were to be had. After considerable experimenting, however, a method was developed by which determinations were made with undisturbed soils in the fields where ground-water plants were growing. The essential steps in the process were as follows: Cylinders of 16-gage galvanized steel were driven vertically downward so as to inclose undisturbed columns of soil. The cylinders were then sealed at the bottom to make them watertight, and they were also protected against evaporation at the top. Measured quantities of water were introduced into or taken from the cylinders, and the resulting rise or fall of the water table was observed.

Altogether nine cylinders were driven—one 18 inches in diameter and 54 inches high, three 18 inches in diameter and 36 inches high, three 12 inches in diameter and 36 inches high, and two 12 inches in diameter and 18 inches high. With the exception of the 54-inch cylinder all were driven nearly to the water table. All were sunk as closely as possible to selected observation wells, and they were put down in the fall, so as to inclose the soils in which the summer water-table fluctuation had occurred.

In order to reach the water table with one of these cylinders a pit 4 by 6 feet was sunk to a level above the water table equal to the height of the cylinder, the proper level being determined by sinking a small test hole to water and making observations with a wye level. The rim at one end of the cylinder was slightly beveled off in order to provide a cutting edge, and a heavy drive cap was provided consisting of short pieces of 3-inch plank under a block of undressed green oak. Operations were begun by placing the cylinder with cutting edge down, after which the cap was placed on its upper end and it was slowly driven downward, care being taken to keep it in a vertical position. Two methods of driving were used with about equal success—in one the cylinder was driven with a maul wielded by one man in the bottom of the pit; in the other, the drive was provided by a pole about 6 inches in diameter and 12 feet long used pile-driver fashion, two men being required to handle it, one in the pit and the other stand-

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ng on a plank over the pit. As the cylinder moved slowly downward the pit was leepened, the bottom of the pit being kept about 6 inches above the lower edge of the cylinder. In this way the friction on the outside of the cylinder was kept it a minimum, and at the same time sufficient support was provided at the bottom to keep the cylinder in a vertical position. When the lower edge of the cylinder reached the water table, the driving was stopped, but the outside excavation was continued until it was slightly below the lower edge of the cylinder. Then with a wire the soil column was sawed off even with the bottom of the cylinder, a bale was attached, and with the aid of a lever the cylinder with its included soil was slightly raised and a bottom was soldered to it. * * * Two small wells were then sunk in the inclosed soil, one to the bottom of the soil column and the other to a somewhat lesser depth. These wells were cased and stopped with cork. Finally the cylinder was provided with a cover to prevent evaporation.

In making determinations of specific yield in these cylinders, water was gradually introduced into the wells until the soil column was saturated practically to the top. Withdrawals were then made until the water table had subsided to the desired position in the column. Then water was alternately taken from or added to the deeper well, and the resulting changes in the water table in both wells were observed. Equilibrium was not established until about 24 hours after the addition of water and about 48 hours after its removal. Pronounced changes in barometric pressure between the time of addition or withdrawal and subsequent water-level observations seriously interfered with the results [table 5]. On this account it was necessary to make the observations in fair weather. Part of the time it was necessary to make corrections for fluctuations in the water table produced by changes in temperature.

Table 5.—*Specific yield of unconsolidated sediments in the Escalante Valley, Utah*

Material	*Specific yield [average] (percent)*
Sandy clay loam	5.3
Loam fill	5.1
Clay fill	4.2
Clay	3.4
Clay loam	2.7
Loam	2.4

Eckis, Rollin, 1934, Geology and ground water storage capacity of valley fill: California Div. Water Resources Bull. 45, p. 91–246.

The results presented cover a period of two and one-half years of field and laboratory investigations. During this time many methods were tried for determining porosity, water retention, and actual water yield of different sediment. * * *.

* * * * * * *

During the course of this investigation, the moisture retention of about 150 samples was determined, four methods of study being used. In general the retention increases with the degree of fineness of the sediment [table 6]. From an analysis of the results, it is concluded that the approximate moisture retention of coarse sediments can be estimated from an index of fineness, called the surface factor, which is determined from the mechanical composition of the sample.

TABLE 6.—*Estimated specific-yield values for sediments of the South Coastal Basin, Calif.*

[Specific-yield values given in percent]

	Gravel				Sand		Clay	
	256+ mm (boulders)	64–256 mm (coarse)	16–64 mm (medium)	8–16 mm (fine)	½–8 mm (coarse and medium)	⅛–½ mm (fine)	Sandy	Clay
Unweathered								
Surface alluvium	(1)...13.6	14.2	20.5	26.5	30.9	21.2	10	1
Subsurface alluvium	(2)...13	14	20	25	28	16	5	1
Weathered subsurface								
Tight [1]	(3)....9	9	13	17	16		------	
Clayey [2]	(4)....4	5	7	8	5		------	
Residual clay [3]	(5)....1	1	1	1	1		1	

[1] Lime-cemented gravels are included in tight gravels.
[2] Lime-cemented sands are included in clayey sand.
[3] The yield of 1 makes allowance for small sandy or gravelly streaks.

Five methods for the determination of specific retention were tried during the course of this investigation. Four of these are direct: (1) laboratory drainage method; (2) collection of samples from well pits and borings; (3) cylinders driven after a rain; and (4) cylinders driven into a material, which is then saturated and drained in the field.

A fifth method, not an independent one, is the estimation of specific retention from a description of the properties of the material (surface factor). * * * Wherever possible, the surface factors have been computed, and the ratio of weight of water retained, to surface factor has been given to facilitate comparison.

The Specific Yield Curve.—Since both the specific retention and the porosity have been shown to vary with size, the computed specific retentions of the individual samples were averaged for each maximum 10 percent grade size and plotted on the graph [fig. 3]. The measured porosities were averaged and plotted in like manner. Values on the specific retention curve were subtracted from corresponding values on the porosity curve to obtain the points through which the specific yield curve was drawn. The specific yield curve gives the average yield value for gravels of which grade sizes of maximum 10 percent of particles are known approximately. This curve can not be used to predict the specific yield of an individual sample. If coarse gravels are considered to be those with maximum 10 percent grade sizes greater than 64 millimeters, the three grade sizes represented give an average specific yield of 14.1 percent for coarse gravel. If medium gravel be considered to occupy that part of the curve with maximum 10 percent between 16 and 64 millimeters, the two grade sizes represented give an average specific yield of 20.6 percent for medium gravels. If gravels the maximum 10 percent of which is 8 to 16 millimeters be considered fine gravels, the average specific yield of fine gravel is 26.5 percent.

* * * * * * *

Specific Yield of the Sands.—From the specific yield curve [fig. 3], the maximum yield of the alluvial series represented is reached in coarse sand (maximum 10 percent size, 1–2 millimeters), and averages about 32.5 percent. The yield for all alluvial sand samples with maximum 10 percent size coarser than ½ milli-

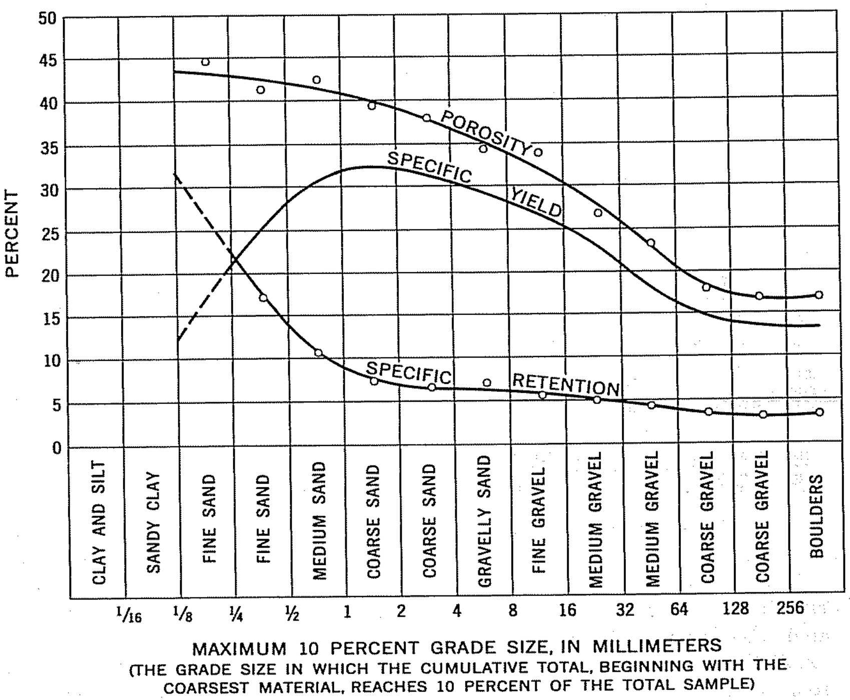

FIGURE 3.—Porosity, specific retention, and specific yield for sediments of the South Coastal Basin, Calif. (After Eckis, 1934.)

meter averaged by grade size is 30.9 percent. These sands are medium to coarse sands, and are considered to be the materials commonly logged as sand and coarse sand by well drillers. The specific yield values for coarse and medium sands were seen to be so nearly the same from the curve, that no attempt was made to differentiate the two for storage capacity computation.

The samples the maximum 10 percent grade sizes of which were greater than ⅛ millimeter and less than ½ millimeter were considered to be fine sands and probably represent the material logged as fine sand or quicksand by well drillers. The specific yield estimated by averaging grade sizes for fine sand is 21.3 percent.

Since the average specific yields of coarse and medium sand were found to differ only a few percent, no attempt was made to assign different yield values for sand in different regions, as was done for gravels. The curve shows an average of 30.9 percent for the coarse and medium surface alluvial sands.

The sand samples used to obtain these specific yield values were taken from cuts or from borings at depths of a few feet below the surface in order to avoid the abnormally high porosities of unburied sands.

* * * * * * *

Specific Yield of the Clays.—Mechanical analyses were made of only a very few of these samples, and therefore the samples were grouped according to maximum grade size by inspection of the grains under a binocular microscope. It was thought from inspection of about 30 samples in this manner that in those the maximum 10 percent grade size of which did not exceed 1/16 millimeter, the

specific retention was generally about equal to the porosity. This lower limit is a rather indefinite approximation, but at any rate the materials classed as sandy clays fall on that part of the specific yield curve lying between 11 percent yield and zero yield. It is thought that these materials are those generally called sandy clays by well drillers. More properly speaking they are very fine sands and silts. The moisture retention and porosity of several samples of sandy clay were obtained from post auger borings at the average depth of a little more than 10 feet. The average computed specific yield of these samples was approximately 10 percent. The specific yields of nine clay samples from post auger holes were computed and found to average approximately zero.

* * * * * * *

Specific yield values have been estimated for the different types of material that fill the freshwater-producing basins, by adaptation of the results of experiments with surface samples to similar materials encountered in wells.

In order to assign specific yield values to the various types of sediments in the ground water basins the unaltered sediments, with their specific yield values shown on [figure 3], were classified into gravel, sand, and clay groups with subdivisions under each. Then the corresponding types of materials encountered in wells were classified under each of these groups, and divided into four stages to represent various degrees of alteration, from fresh material to residual clay. The specific yield of each type for each stage of alteration recognized was estimated from the yield of its unaltered derivative. The classification with the yield values is shown in table 6.

The Unweathered Deposits.—Line 1, table 6, gives yield values averaged from the specific yield of the unaltered gravel curve [fig. 3]. These values having been derived from practically unaltered surface samples could not be directly applied to the subsurface materials. Line 2 gives the specific yields estimated for subsurface unweathered materials. These values were modified from those of Line 1, because of settling.

The gravel values were reduced only slightly, as it seemed probable that the effects of settling, greatest in sand and clay, would become less with coarser materials and probably practically die out with very coarse poorly sorted gravel and boulders. Thus the specific yield of coarse to medium gravels was reduced an average of five-tenths of one percent (to the nearest whole number), fine gravel 1.5 percent, coarse and medium sand 3 percent, fine sand and sandy clay each about 5 percent. From Curves I and II, of [figure 4], the loss of porosity from the surface to the depth of 50 feet appeared to be about 5 percent porosity. The depth of 50 feet, being below the steepest part of the curves, was thought to represent a fair average for the amount of compaction, and to take into account practically all of the near surface consolidation due to settling. It seems that lowering the specific yield of these materials (fine sand and sandy clay) 5 percent is conservative, since the specific yield may drop even more than the porosity. The values for coarser sands and gravels, though not measured, were reduced correspondingly less, estimates in all cases being made to the nearest whole number.

These subsurface values (Line 2, table 6), estimated from the surface sample averages, represent the unweathered materials of the water-producing section and include such types logged by well drillers, as loose water gravel and loose or running sand, which are the best water-yielding sediments of the formation.

* * * * * * *

The well samples showed significant size differences fom surface gravels only at considerable distances from the mountains and in the regions where the gravels

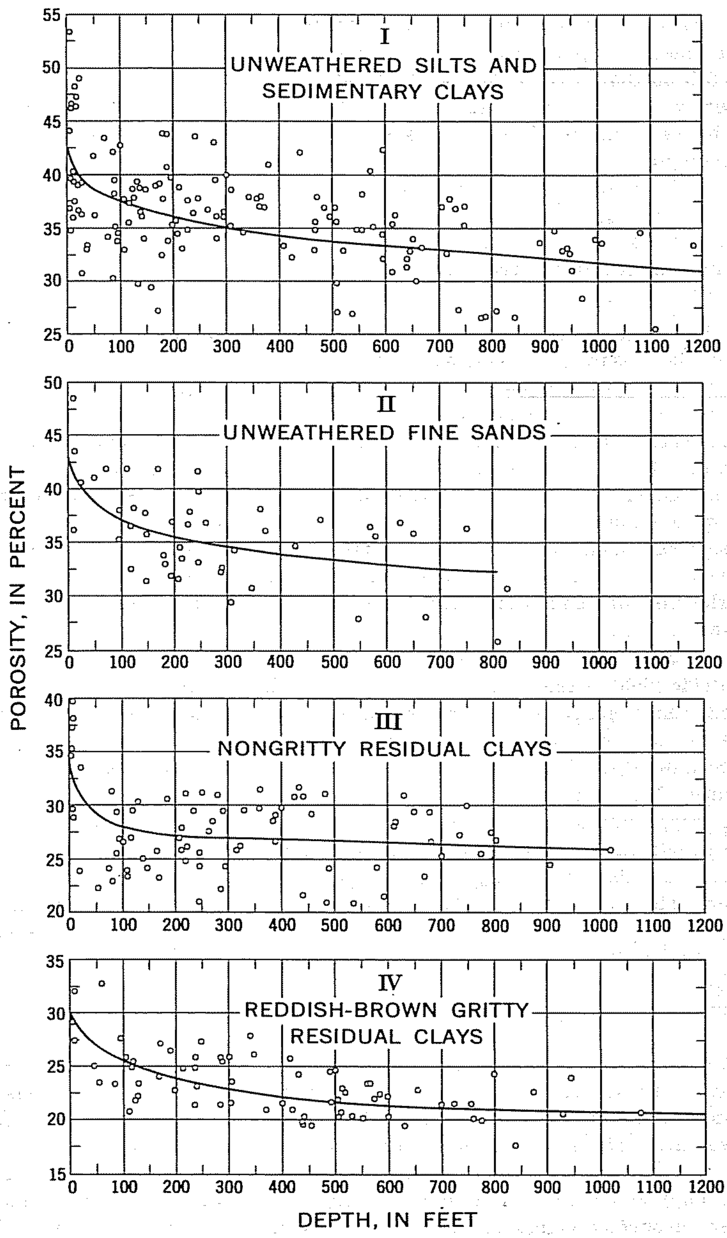

FIGURE 4.—Relation of porosity to depth in certain types of sedimentary materials of the South Coastal Basin, Calif. (After Eckis, 1934.)

were interbedded with sands and fine gravels. In these areas the materials on the surface do not represent the true average coarseness because the coarser gravels are usually covered by finer material deposited during the later stages of flood. The well samples were, in such cases, relied upon for size estimates. Values

for practically the entire coastal plain were determined in this manner. Well samples were not available for large parts of the upper slopes of the basins and in these areas it was necessary to apply the surface size distribution to the buried materials. The two were thought to be comparable because no significant average size differences were noted between surface and depth conditions where well samples were obtained from the regions of coarse gravel.

Although well samples showed some differences in gravel sizes at different depths, the data were not complete enough to make possible the assignment of correspondingly different values. This inaccuracy is thought to be unimportant since doubling the maximum 10 percent size changes the specific yield only a few percent, and well samples seldom indicate consistent size changes of one grade size with change of depth.

* * * * * * *

The Weathered Deposits.—Since all variations in specific yield from those of the unaltered deposits, to zero for residual clay, occur in weathered deposits, it was found necessary to make an arbitrary classification for the purpose of assigning specific yield values.

The specific yield of weathered gravels and sands depends on: (1) the specific yield of the unweathered deposit, and (2) the extent to which alteration has progressed. Slightly weathered gravels and sands that have retained their original structure are generally classified as tight gravels or tight sands by well drillers. Gravels and sands that have lost a large part of their original structure but retain resistant pebbles or cobbles embedded in a clayey sandy matrix are generally classed as gravelly clays and sandy clays. Gravels and sands that have been altered to red, brown, or gray clayey soils with gritty angular residual fragments embedded, are usually called clay by well drillers. These classifications were adopted and specific yield values assigned accordingly.

The specific yields of the weathered materials could not be successfully classified from measurements on actual samples because of the nature of variation. Therefore specific yields were assigned by making an arbitrary division according to the degree of alteration. Tight gravel was given a yield value of two-thirds that of unweathered subsurface gravel, and gravelly clay, one-third the specific yield of unweathered gravel. Probably the typical residual clay has a yield of zero, but since it is highly variable in composition it undoubtedly contains streaks that yield small quantities of water. It was, therefore, assigned a specific yield of one to indicate a probable slight yield throughout the well section.

The estimation of yield values for weathered sand was less simple. It was found that the decomposition of sand reduced the specific yield sharply, so that materials logged as tight sand had a specific yield value less than two-thirds that of good sand. Sandy clay formed by decomposition, being similar in mechanical composition to unweathered sandy clay, probably has an average specific yield similar to that of unweathered sandy clay.

Since unaltered sands were classified according to coarseness, as sand, fine sand and sandy clay, the two finer divisions were so similar to tight sand and sandy clay (weathered) that it was impossible to separate them in well logs. Therefore the value of 16 percent assigned to fine sand was used also for tight sand, and all sandy clays were considered to yield 5 percent.

Lugn, A. L., and Wenzel, L. K., 1938, Geology and ground-water resources of south-central Nebraska: U.S. Geol. Survey Water-Supply Paper 779, p. 89–96.

In the laboratory the samples of water-bearing material are saturated and subjected to a centrifugal force approximately 1,000 times the force of gravity. The samples are weighed, then dried and reweighed. The difference in weight represents the weight of the moisture that is retained after centrifuging. The moisture equivalent by weight is computed by dividing the weight of the moisture retained after centrifuging by the weight of the dry soil, and the moisture equivalent by volume is computed by multiplying the moisture equivalent by weight by the apparent specific gravity of the material.

The moisture-equivalent determinations are made to ascertain the specific retention [Meinzer, 1923b]—that is, the quantity of water that a soil or rock will retain against the pull of gravity if it is drained after having been saturated, expressed as the ratio of the retained water to the total volume of material. The specific yield of a material is equal to the porosity minus the specific retention. * * *.

* * * * * * *

Tests for moisture equivalent were made on four samples of loess obtained in the Platte Valley near Lexington. * * * The average moisture equivalent by volume was 33.8, and the average porosity was 53.7. If the average moisture equivalent is taken to represent the average specific retention, the average specific yield of the four samples of loess is about 20 [table 7].

* * * * * * *

TABLE 7.—*Specific yields of water-bearing sediments in the Platte River valley, Nebraska*

Material	*Specific yield (percent)*
Sand and gravel	24
Silt (loess)	20
Clayey silt	13

The moisture equivalent of samples of the Pleistocene sand and gravel obtained near Grand Island, Kearney, and Lexington was also determined in the laboratory. * * * One sample was composed principally of clay, and its moisture equivalent was 27.1, and the specific yield 13.2. * * * The moisture equivalents of * * * 17 samples ranged from 1.9 to 3.9 and averaged 2.8. This average falls into the range where Piper found that the moisture equivalent was considerably less than the specific retention. By using his diagram, the specific retention corresponding to a moisture equivalent of 2.6 is found to be about 5. The porosity of the 17 samples of sand and gravel ranged from 21.5 to 41.8 and averaged about 29. The average specific yield is therefore computed to be 29 minus 5, or 24.

* * * * * * *

The moisture equivalent was determined also for several samples of soil in the vicinity of Lexington. Most of the soil is developed from loess and therefore may be expected to possess similar hydrologic properties. * * * The specific yields of these samples are 4.4 and 21.7 respectively. * * *.

A pumping test was made on the farm of Fred Meyer, about 4 miles west of Grand Island, * * * and the specific yield of the water-bearing sand and gravel was determined in place. The method was suggested by Meinzer [1932] and consists of determining the ratio of (1) the quantities of ground water which in a given time are taken from storage between concentric cylindrical sections around the pumped well to (2) the volume of sediments between the cylinders that are unwatered in that time. * * *.

* * * * * * *

The computed specific yield became larger as the pumping increased, for the reason that all the water in the material does not drain out of it immediately. When pumping starts, a comparatively large volume of material is unwatered, partly because only a small percentage of the water contained in the interstices of the sediments immediately drains down to the water table. As pumping is continued, more water gradually drains out of the unwatered sediments, and hence the specific yield computed from the first few hours of pumping is relatively small. The specific yield computed from the volume of water-bearing material unwatered in the last few hours of pumping would be too large because of the addition of water that percolated down from the material previously unwatered. The average results for specific yield * * * plotted against the periods of pumping, fall on a smooth curve. By extending this curve the conclusion is reached that the true specific yield lies between 22 and 23.

The specific yield determined by this test applies only to the upper few feet of water-bearing material that was unwatered during the period of pumping. A sample of water-bearing material from the well drilled at the location of this test was obtained close to the water table. * * * The porosity was found to be 27.1 and the moisture equivalent 2.6 in the hydrologic laboratory. Piper's relation between moisture equivalent and specific retention gave a specific retention of about 5, from which the specific yield is computed to be about 22.

Piper, A. M., Gale, H. S., Thomas, H. E., and Robinson, T. W., 1939, Geology and ground-water hydrology of the Mokelumne area, California: U.S. Geol. Survey Water-Supply Paper 780, p. 101–121.

Two methods have been used to determine the specific yield of typical water-bearing materials of the Mokelumne area—(1) measuring the volume of material saturated and unwatered by alternate addition and withdrawal of measured volumes of water from columns of undisturbed soil; and (2) determining the difference between the porosity and the specific retention of samples of undisturbed material after drainage for periods as long as 390 days. These are * * * termed, respectively, the volumetric method and the drainage method.

* * * * * * *

In the [volumetric] tests * * * the mean elapsed time ordinarily ranged between 19 and 63 days. The shorter term was perhaps inadequate for equilibrium to be fully attained, but in contrast, the three columns for which the elapsed time was least * * * also afford results for specific yield after the lapse of 215 to 220 days and without further withdrawal or addition of water. The longer term increased the specific yield between 1 and 3 percent of the result derived from the shorter term. However, these three columns were coarse in texture; the increase in yield with longer term might well have been greater had the material been finer. * * *.

Obviously, the lapse of time required for the water level to reach true equilibrium at any particular temperature depends largely upon the lag in replenishing the capillary fringe as water is added and in draining the fringe as water is withdrawn. In either case, the volume of material saturated or unwatered tends to diminish as the term of the test is lengthened—that is, the result for specific yield tends to increase. All the columns of material tested in the Mokelumne area have tended to give larger results for specific yield by saturation than by unwatering, whence it is inferred that the lag following withdrawal is the greater. For example, among four columns tested in 1930 and 1931, the respective mean

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results for determinations by saturation are between 108 and 115 percent of the mean results for alternate determinations by unwatering, the particular materials being relatively coarse. That the range might have been much greater for fine materials is suggested by the determinations for column 3626N in 1928–29. For that column, two results for specific yield by saturation were about three times as large as two results by unwatering, although all were small. The experimental errors due to lag seem not to compensate in short-term tests which withdraw and add equal volumes of water alternately. Further, if the columns are too short to contain the full capillary fringe, the results for specific yield tend to be too small, and the error becomes progressively greater as the stage of the water table is raised in the column. All the foregoing considerations suggest that the respective average specific yields determined by the volumetric method are likely to be less than the true specific yields of similar materials in the field.

Figure 5 shows the relation between the results for specific yield as determined by the drainage method and the mean size of the particles composing the respective samples. On that diagram the abscissas allot equal space to successive grades or classes whose limiting particle sizes are in the constant ratio 2:1; thus the silt fraction of the conventional nomenclature spans 3.6 classes, and the clay fraction is extended indefinitely. With three exceptions, the plotted points fall within a moderately narrow zone with parallel straight-line limits as indicated, the width of that zone being equivalent to one class interval. Without exception, the points that represent materials with small dispersion of particle sizes (standard size-ratio deviation is small) fall to the right on the diagram; likewise, the points that represent the materials of higher porosity for any particular mean size and size-ratio deviation fall to the right. These relations suggest that the specific yield of these particular water-bearing materials is a systematic function of mechanical composition and texture, although obviously the 16 tests just described afford too few data for statistical treatment of that suggestion.

The drainage tests on the second set of samples * * * were terminated after about a year (322 to 390 days). In all the samples the quantity of retained water decreased steadily, though at a diminishing rate. Thus, the retention at the end of the tests ranged between 61 and 97 percent of the respective quantities retained after the lapse of 96 to 111 days; also, in general, the greater additional drainage came from the coarser-grained samples. * * * The specific yields derived from the longer term of drainage ranged between 106 and 167 percent of the respective results derived from the shorter term and averaged 127 percent. In general, the percentage increase was least for the materials of large specific yield and greatest for the materials of moderate specific yield.

The percentage increase in the results for specific yield derived from the longer term of drainage is greater than the increase in the few long-term tests by the volumetric method. However, it has been inferred that the volumetric method tends to yield results that are too small, whether the test is made by saturation or by unwatering, although the tests by saturation have consistently afforded results somewhat greater than those by unwatering. Accordingly, the increased yield indicated by the long-term drainage tests may measure the actual behavior of water-bearing materials under field conditions, whereas tests by the volumetric method as conducted in the Mokelumne area may not evaluate the final small increments of specific yield.

The graphs that constitute figure 6 show the mean specific retention of the materials tested by the drainage method in relation to their moisture equivalent, a property that has been used commonly as an approximate measure of the quantity of water that a material would retain against the pull of gravity. The graphs are based upon the two sets of axial subsamples taken from the respective gross samples after the two terms of drainage. * * *

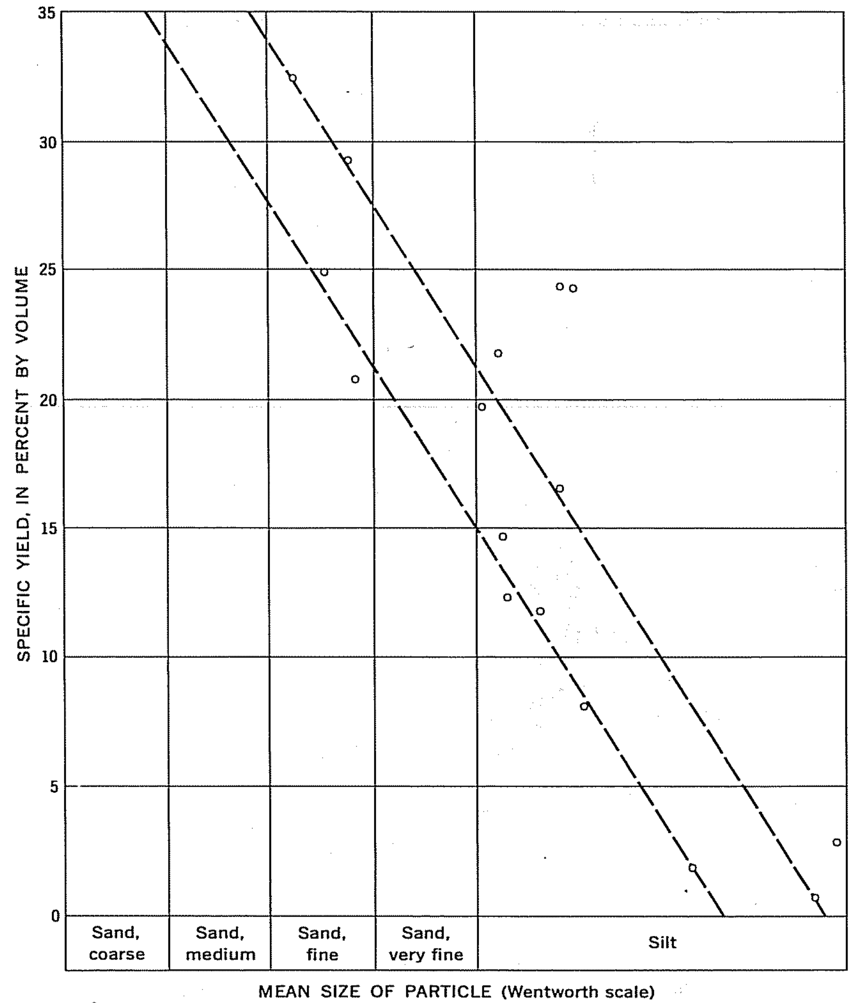

FIGURE 5.—Relation between texture and specific yield of materials that were drained for approximately 100 days. (After Piper and others, 1939.)

* * * * * * *

Records for 231 irrigation wells within the area that receives percolate are available in sufficient detail to show the physical character of the material in the two zones. Of these, 185 wells have driller's records, which commonly discriminate three general classes of material—"gravel" and "coarse sand," "sand" or "standing sand," and "silt" or "clay." The remaining 46 wells have yielded samples that have been classified according to the standard grades or classes of granular material. * * * By comparing the two sorts of records for several

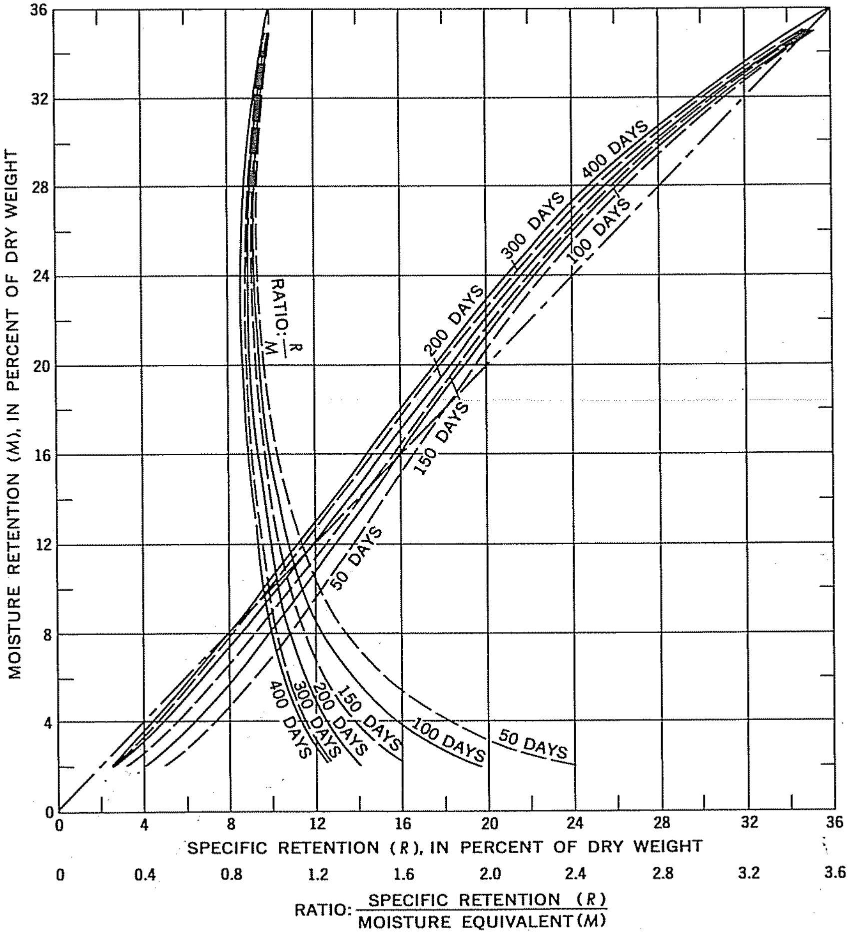

Figure 6.—Relation between moisture equivalent and specific retention of water-bearing materials that were drained for 50–400 days. (After Piper and others, 1939.)

wells within selected small areas approximate correlations have been derived as follows: (1) By "gravel" and "coarse sand" the driller designates material whose dominant grade falls under one or the other of those same terms in the standard classification—that is, material in which most particles are larger than 0.5 millimeter in diameter; (2) "sand" and "standing sand" span the medium-sand and fine-sand grades of the standard classification—that is, they include material in which the dominant fraction is 0.5 to 0.125 millimeter in diameter; (3) "silt" and "clay" include the very fine sand, the silt, and the clay fractions of the standard classification—that is, material composed largely of particles smaller than 0.125 millimeter in diameter. * * * Corresponding mean results for specific yield determined by the drainage method are interpolated from figure 5 as follows: Gravel and coarse sand, 35 percent; medium and fine sand, 26 percent; very fine sand, silt, and clay, 3.5 percent [table 8].

Table 8.—*Specific yields of water-bearing sediments of the Mokelumne area, California*

Material	*Specific yield (percent)*
Gravel and coarse sand	35
Medium and fine sand	26
Very fine sand, silt, and clay	3.5

Wenzel, L. K., 1942, Methods for determining permeability of water-bearing materials: U.S. Geol. Survey Water-Supply Paper 887, p. 110, 100.

It is generally recognized that saturated water-bearing materials when allowed to drain, may yield water rather slowly. Investigations have shown that a sample of material after being saturated may continue to drain for several years, although most of the water in it may drain out in a much shorter time. Thus the value for the specific yield of a material, as ordinarily determined in the laboratory, is not likely to be reached under conditions found in nature except when the water-bearing material is permanently unwatered. Hence, material that is unwatered and then saturated again may hold in the period when it is unwatered considerably more water than is represented by the specific retention of the material.

The slow draining of water-bearing material in the vicinity of a pumped well causes the water table to decline rapidly at first and then more slowly as draining proceeds. * * *.

* * * * * * *

Although the material may yield a very large percentage of the water in it in a few hours or days, it may continue to yield small amounts for several years. The sand and gravel unwatered during a pumping test near Grand Island, Nebr., drained in such a manner that the computed specific yield of the material was 9.2 after 6 hours of pumping, 11.7 after 12 hours, 16.1 after 24 hours, 18.5 after 36 hours, and 20.1 after 48 hours of pumping [fig. 7]. A much longer period of pumping would be required before the true specific yield of the material would have been reached. The true specific yield was estimated to lie between 22 and 23. [See Lugn and Wenzel, 1938.]

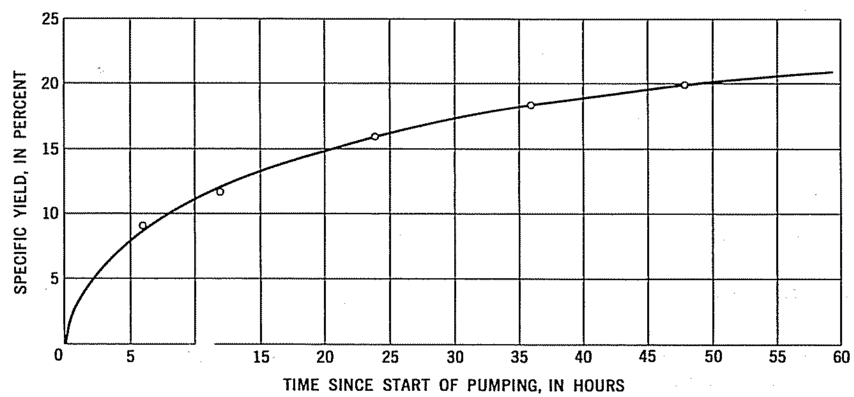

Figure 7.—Variation of specific yield in relation to duration of pumping for a pumping test at Grand Island, Nebr. (Graph prepared by A. I. Johnson with data from Wenzel, 1942, p. 100.)

Wenzel, L. K., Cady, R. C., and Waite, H. A., 1946, Geology and ground-water resources of Scotts Bluff County, Nebraska: U.S. Geol. Survey Water-Supply Paper 943, p. 66–67, 86.

The Brule formation * * * is chiefly a ruddy-buff, or flesh-colored silt, massive and featureless in fresh exposures, but weathering into brick-shaped blocks or slabs. * * *.

* * * * * * *

Eighty-eight percent of the material was composed of very fine sand and silt, and almost 70 percent was silt. * * *.

* * * * * * *

The moisture equivalents determined in the laboratory for the two samples taken from the Brule formation were 24.9 and 20.9, respectively, an average of 22.9. Because the values fall in the higher range referred to by Piper, they can be taken to represent the approximate specific retention. The porosities of the samples were 51 and 54, an average of 52.5. Thus the average specific yield of the samples is 29.6. This indicates that a cubic foot of Brule, if allowed to drain for a long period will yield about 0.296 cubic foot of water and will retain about 0.229 cubic foot.

Investigations have shown that a sample of material after being saturated will not yield its water at once but the water will drain rather slowly, the rate of draining being somewhat proportional to the permeability of the material. The Brule, because of its tight character, yields water sluggishly, and several months to a year or more are doubtless required before the specific yield calculated in the laboratory is reached. As a result the quantity of water that is removed from storage by a decline of the water table in the Brule cannot be calculated from the specific yield determined in the laboratory unless the water table remains below the material for a long period. The comparatively large seasonal fluctuation of water levels in wells that tap the Brule results in part from the incomplete draining of the material during the time allowed. This means that the water table may decline for a considerable period before much water comes out of storage, except what drains from the cracks and fissures. This decline, however, will gradually slow up as the water table reaches lower stages, and a greater thickness of the formation thereby becomes available for draining.

Poland, J. F., Davis, G. H., Olmsted, F. H., and Kunkel, Fred, 1951, Ground-water storage capacity of the Sacramento Valley, California, Appendix D *of* Water resources of California: California Water Resources Board Bull. 1, p. 624–627.

In order to estimate the storage capacity of the water-bearing deposits it was necessary to classify the materials in the drillers' logs into a few groups to which arbitrary specific yield values could be assigned. Although many of the logs reported only gravel, sand, or "clay" (actually silt in most places), or gradations between these primary units, other logs reported as many as 10 to 20 different types of material. After a review of the many types of material described, it was decided to group the materials logged in five general classes, namely: (1) gravel; (2) sand, including sand and gravel, and gravel and sand; (3) tight sand, hard sand, or sandstone, with which were combined 26 different drillers' terms covering material with more or less similar hydrologic properties; (4) cemented gravel, or clay and gravel, which embraced 19 additional drillers' terms; and (5) "clay," which included 19 different types of material ranging from silt through clay to shale, and included lava. To obtain a reasonable geographic distribution of logs, the same well logs previously selected for the peg model on the basis of depth and representative geographic distribution also were utilized for the classification of materials. Thus, for approximately 3,000 well logs, materials were classified in the five general classes described above.

Assignment of Specific Yield Values.—It was not feasible to make an extensive field investigation to determine the specific yield of the different types of water-bearing materials in the Sacramento Valley. Therefore, it was necessary to assign an estimated specific yield value to each of the five general categories of material on the basis of available data.

* * * * * * *

On the basis of the results obtained in * * * two investigations [Eckis, 1934; Piper and others, 1939], together with specific-yield data from less detailed studies by others, * * * specific-yield values were assigned to the five groups of material classified in the well logs of the Sacramento Valley [table 9].

TABLE 9.—*Specific yield of water-bearing sediments in the Sacramento Valley, Calif.*

Material	*Specific yield (percent)*
Gravel	25
Sand, including sand and gravel, and gravel and sand	20
Fine sand, hard sand, tight sand, sandstone, and related deposits	10
Clay and gravel, gravel and clay, cemented gravel, and related deposits	5
"Clay," silt, sandy clay, lava rock, and related fine-grained deposits	3

For the purpose of estimating underground storage capacity, the Sacramento Valley was divided roughly into four storage groups and these in turn were subdivided into a total of 29 storage units, as shown on figure 8. The subdivision into groups and into the smaller storage units was first made areally from physiography and soils; that is, from what can be seen at the land surface; then the boundaries of the units were modified on the basis of the subsurface geology to a depth of 200 feet, as shown by the peg model. In the modification, special emphasis was placed on the hydrologic character of the sediments and the continuity of water-bearing beds in the top 100 feet (the upper and middle zones).

This was done for three reasons. First, it is believed that the storage units should be representative for the depth range most widely subject to unwatering or resaturation under present conditions or under moderately increased utilization to be anticipated in the near future. Second, for nearly all the storage units in the valley except the basin deposits, the specific yield is greater above the 100-foot depth than below it. Lastly, with reference to natural or artificial recharge at or near the land surface, the distribution of water-bearing beds in the near-surface deposits is of primary importance. In this respect, the coarse gravel tongues or blankets that are so well defined at shallow depths beneath the channels of Cache Creek (A1), and the Feather River (A5), are especially noteworthy.

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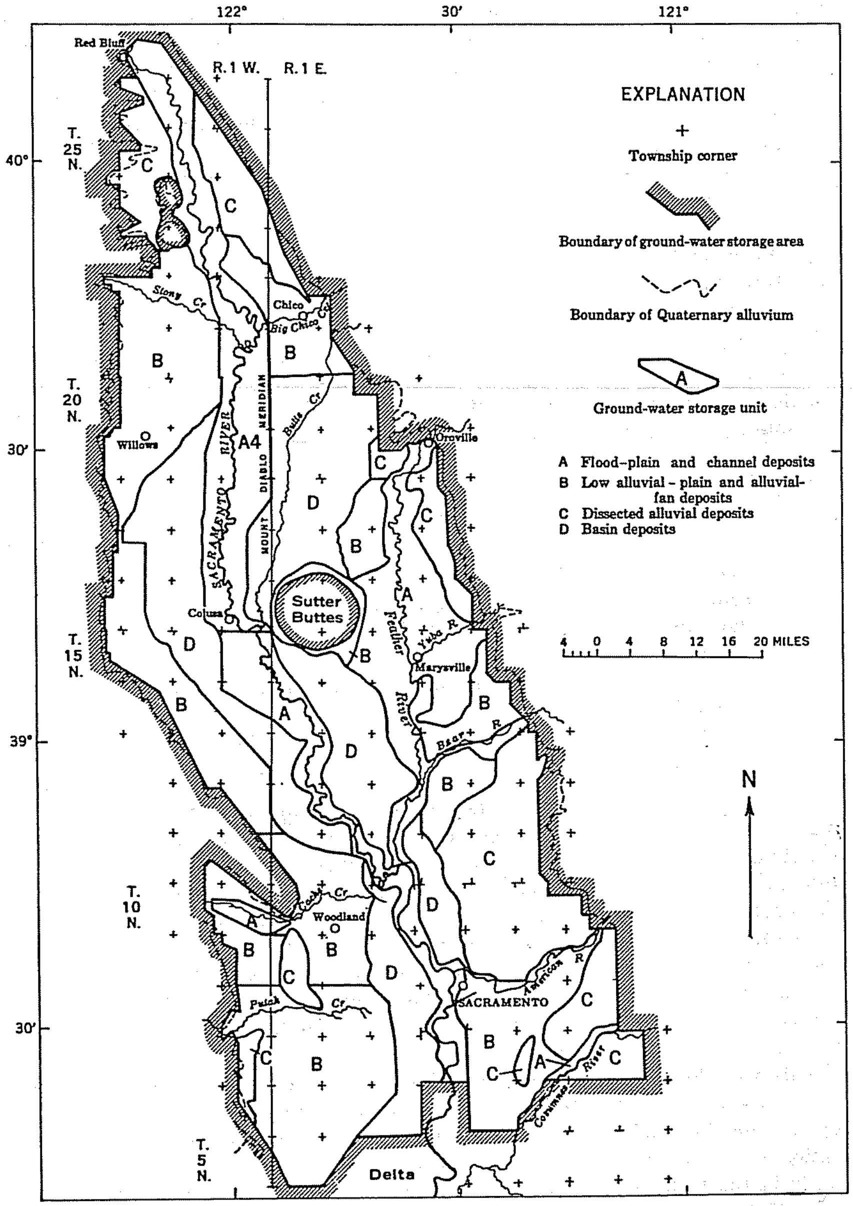


FIGURE 8.—Ground-water storage units of Sacramento Valley, Calif. (After Poland and others, 1949.)

Computation of the ground-water storage capacity of the Sacramento Valley involved the following steps:

1. The valley deposits were divided areally into four storage groups and these were subdivided into 29 storage units.

2. For each of the 29 units the area within each township or portion of a township included was measured to the nearest 10 acres with a scale or planimeter. The township or part of a township became the basic subunit for computation of storage capacity.
3. For each of three depth zones under consideration (20–50, 50–100, and 100–200 feet below land surface), logged material in selected wells in each basic subunit was classified into five categories of material. An arbitrary specific yield was assigned to each category.
4. Using these arbitrarily assigned specific-yield values, the average specific yield was computed for each depth zone in each basic subunit.
5. The storage capacity (to the nearest 100 acre-feet in each subunit was obtained as the product of average specific yield times volume of sediments in the depth zone.
6. Storage capacity for each storage unit was obtained as the sum of storage in all the subunits. These were then totaled by groups to give the estimated ground-water storage capacity for the Sacramento Valley.

Upson, J. E., and Thomasson, H. G., Jr., 1951, Geology and water resources of the Santa Ynez River basin, Santa Barbara County, California: U.S. Geol. Survey Water-Supply Paper 1107, p. 130–133.

The decline of shallow water level during the summer is a measure of the total discharge during that period. * * * The seasonal decline varies from year to year, apparently mainly in response to rainfall. The largest declines occurred after the 1938 and 1941 winters of excessive rain when pumpage was small, and probably are accounted for by relatively large seepage to the river in the ensuing summer seasons. * * * However, the average for the entire plain in tne period 1935–44 is taken as 3.5 feet.

To determine the quantity of water represented by this decline of water level it is necessary to determine a value for the specific yield of the materials within the zone of water-level fluctuation. Specific yield is estimated approximately from the physical composition of the deposits by using a method similar to that employed by Piper (Piper, Gale, Thomas, and Robinson, 1939, p. 120–121) in the Mokelumne area. This method utilizes independently determined values for the specific yield of different grade sizes of material, together with the proportionate volumes of different sizes as revealed by well logs. * * *.

The total footage of each of several types of material within the determined range of water-level fluctuations was obtained from well logs. The types are designated according to the drillers series, and are grouped into four main classes as follows: Gravel and coarse sand; sand; silt, including fine sand, sandy clay, and soft clay; and clay [table 10]. * * * Next, the total footage of the different classes of material as recorded in drillers' logs and Survey logs were added by areas, making allowance for a preponderance of wells bored in the coarse channel deposits; and new percentages were obtained. The percentages were weighted according to the acreage of the several areas and the following percentages by volume of the four classes of materials within the range of water-table fluctuations over the entire Lompoc plain obtained: Gravel and coarse sand, 7 percent; sand, 23 percent; silt, 32 percent; and clay, 38 percent.

The terms applied by drillers apparently correspond in general to standard terminology for grain sizes. By referring to the report on the Mokelumne area (Piper, Gale, Thomas, and Robinson, 1939, p. 117, fig. 8), the following values of specific yield for the grade sizes distinguished were taken: Gravel and coarse

TABLE 10.—*Specific yields for water-bearing sediments in the Lompoc plain, Santa Barbara County, Calif.*

Material	*Specific yield (percent)*
Gravel and coarse sand	35
Sand	30
Silt, including fine sand, sandy clay, and soft clay	12
Clay	2

sand, 35 percent; sand, 30 percent; silt, 12 percent; and clay, 2 percent. Applying these values in proportion to the percentage volumes of the different classes of material, the average specific yield of the deposits within the zone of water-table fluctuation in the Lompoc plain is computed to be 14 percent.

Taking the total area as 16,300 acres, the average specific yield as 14 percent, and the average yearly decline as 3.5 feet, the amount of water represented by the decline is about 8,000 acre-feet a year. This represents the total amount discharged during the season of no replenishment, or about half the year. Some discharge also occurs in winter, but its effect is masked by recharge. * * *.

Klein, I. E., written communication: Sacramento, Calif., U.S. Bureau of Reclamation.

[Table 11 and figs. 9 through 12 illustrate the relation between texture and hydrologic properties, as determined by I. E. Klein.]

TABLE 11.—*Specific yield (or effective porosity) of core samples from Bureau of Reclamation test holes in the Friant-Kern Canal service area, as determined from measured porosities and moisture equivalents*

Hydrotextural classification	Number of tests	Specific yield		
		Mean	Median	Range of 90 percent
Well-sorted fine sand	127	30	30	18 –37
Well-sorted medium sand	130	30	30	23 –35
Well-sorted coarse sand	35	29	30	25 –33
Ill-sorted fine sand	204	14	13	4 –25
Ill-sorted medium sand	123	20	21	9 –30
Ill-sorted coarse sand	44	23	23	13 –29
Well-sorted silt	122	13	12	½–28
Very ill sorted silty sand	329	5	4	½–15
Ill-sorted silt	372	3	2	½–11
Clayey sediments	446	1	½	0 –2
Diatomaceous clayey sediments	34	½	½	0 – ½

California Department of Public Works, 1956, Santa Margarita River Investigation: California Div. Water Resources Bull. 57, v. 2, app., p. B65–B67.

In general, the procedure adopted followed that prescribed by the Division of Water Resources in its South Coastal Basin Investigation. Briefly, this method entailed estimating the volumes of various sedimentary types such as sand, gravel, clay, etc., occurring within appropriate depth intervals in each basin, multiplying each of these volumes by an appropriate weighted specific yield factor to obtain the volume of extractable water contained in each interval and finally summing the capacities of each interval to obtain the total storage capacity of the basin. Specific yield is defined herein as the volume of extractable

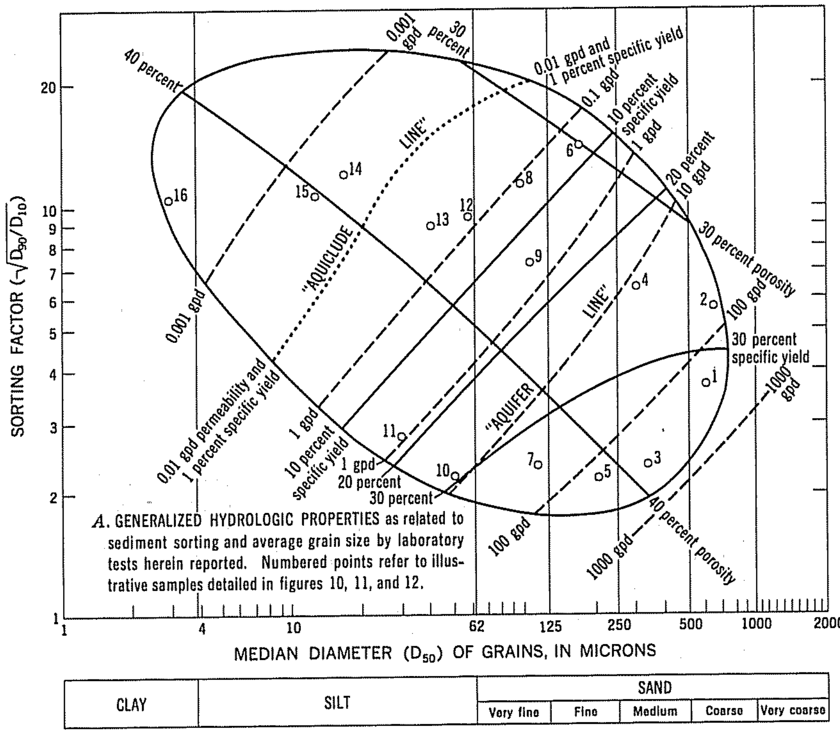
ground water obtained from a unit volume of material expressed as a percentage of the volume of the material.

The logs of water wells provided the information upon which the storage capacity estimates were based. Clay, sand, and gravel and numerous gradations between these types were recognized on most logs. Some logs reported as many as 20 different types of material. In order to estimate the storage capacities of individual sedimentary types, it was first necessary to assign a specific yield value to each type appearing on the logs. The values assigned are those set forth in table 12 and were derived largely from laboratory determinations made at the time of the South Coastal Basin Investigation.

TABLE 12.—*Specific yield of water-bearing sediments in Santa Margarita Valley, Calif.*

Type	Description of material		Specific yield value assigned
Clay	Carbonaceous-silt Decomposed granite Hill formation	Hardpan Adobe	1
Soil	Loam Lake bed		4
Clay-sand	Sand and clay Muck Sea mud and packed sand Silty clay Clay with lime rocks	Cement Sandy clay Cemented sediment	5
Silt	Sandy soil		10
Sand	Fine sand	Coarse sand Quicksand	28
Tight sand	Sandy-soil Silty-sand Unsorted angular sand Sand with trace of clay Sand and mud	Cemented sand Dirty sand	16
Gravel	Gravel and sand Boulders Cobbles and sand Fill		22
Tight gravel	Cemented gravel Gravel with clay layers Dirty gravel	Sandy clay with gravel Packed sand with rocks	15
Gravel Clay	Conglomerate (partially cemented) Clay and boulders		7

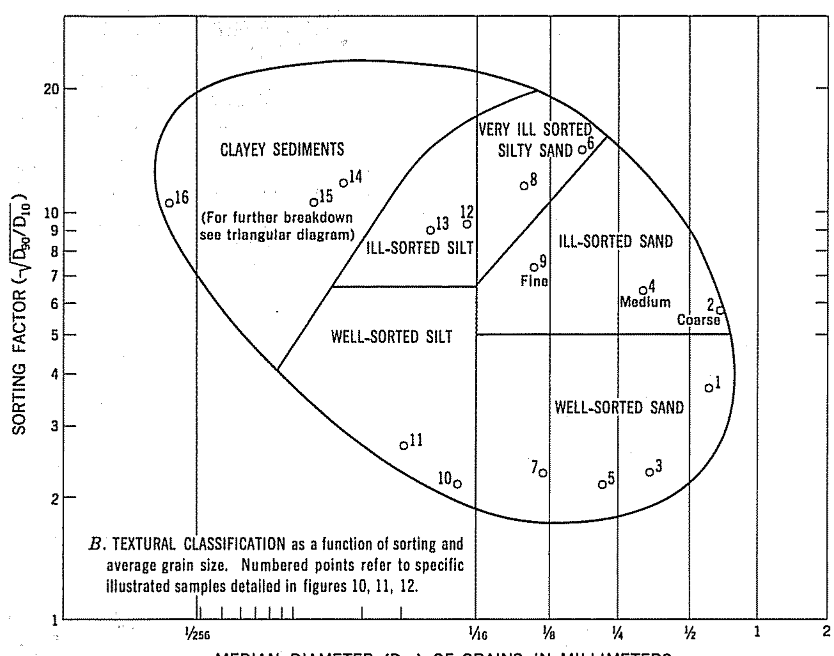
Estimates of the storage capacities of ground water basins are necessarily approximate because of inherent difficulties in extending data from relatively few wells to apply to entire basins. The results, however, are believed to be use-



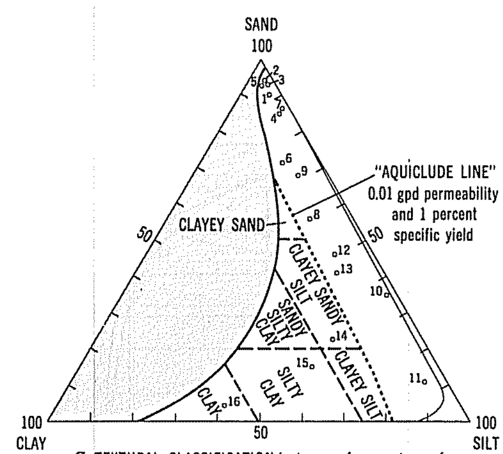
A. GENERALIZED HYDROLOGIC PROPERTIES as related to sediment sorting and average grain size by laboratory tests herein reported. Numbered points refer to illustrative samples detailed in figures 10, 11, and 12.

NOTES:

1. The oval fields of graphs *A* and *B*, and the unshaded area of graph *C* include more than 95 percent of the more than 1,000 core samples on which laboratory tests have been made. The hydrologic-property curves of graph *A* are based on the results of more than 500 tests which they generalize and summarize. The general order of precision of correlation is illustrated by specific examples of figures 10, 11, and 12.
2. Gravels, though hydrologically important, are restricted to the upper part of the major fans and are not represented here because undisturbed cores were not secured; the less significant weathered sands also are not shown. The relation of texture to the hydrologic properties of the weathered sediments is less definite and sometimes at variance with these graphs, especially for those sediments in which hardpans were formed. Other materials whose properties are not fully evident from these graphs are highly diatomaceous clays, firmly cemented calcareous sediments, and marls.
3. As shown on illustrations; gpd=gpd per sq ft.

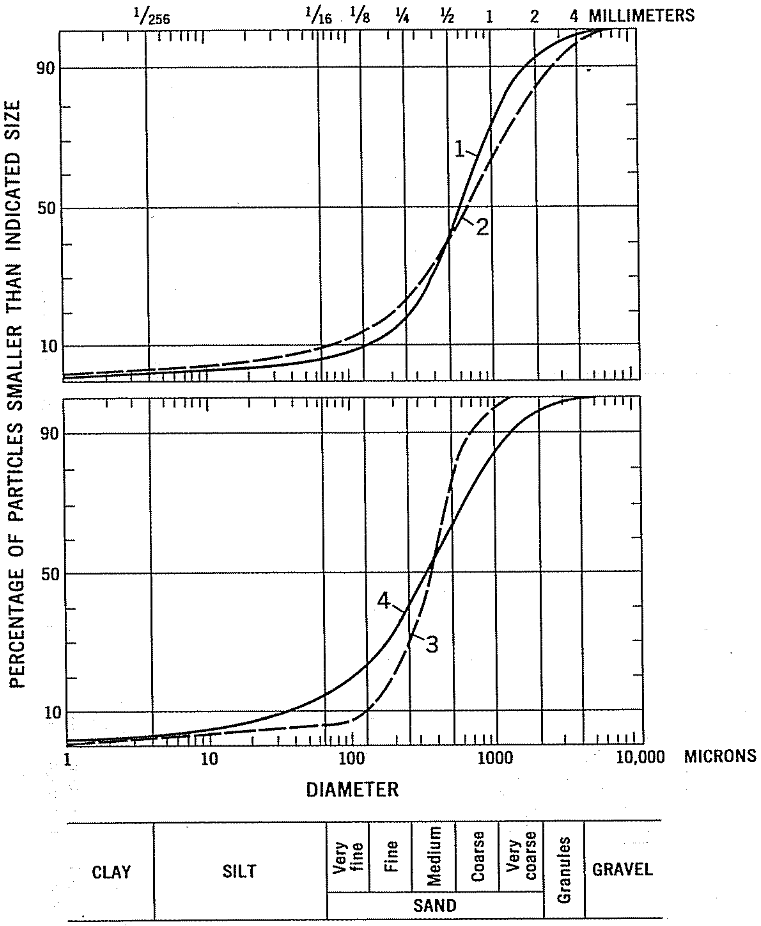


B. TEXTURAL CLASSIFICATION as a function of sorting and average grain size. Numbered points refer to specific illustrated samples detailed in figures 10, 11, 12.



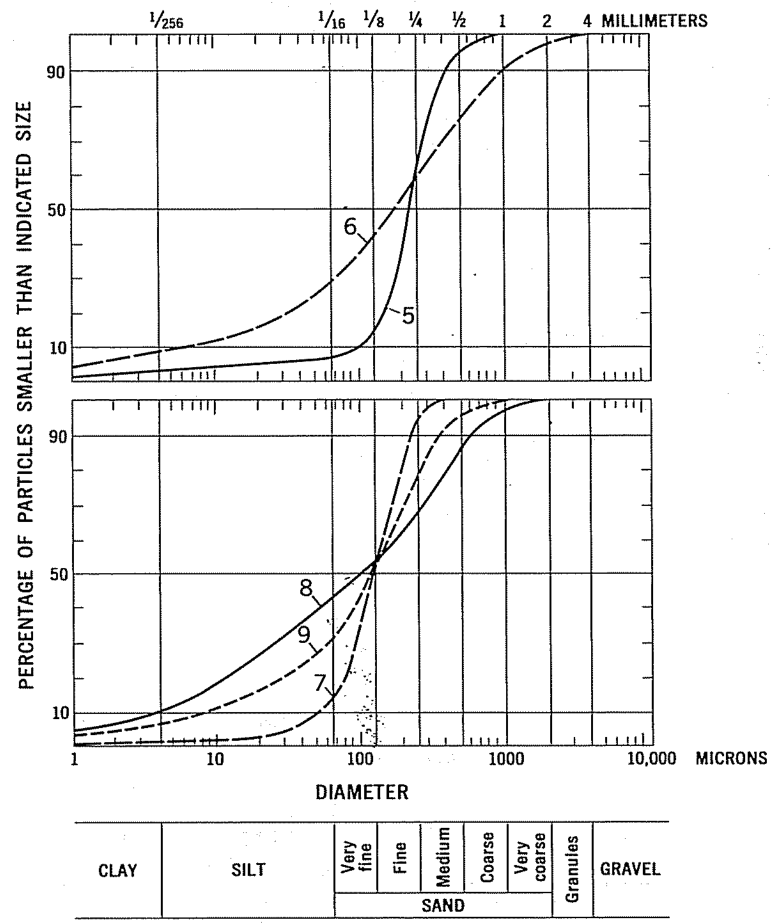
C. TEXTURAL CLASSIFICATION in terms of percentage of sand, silt, and clay. Numbered points refer to sediments detailed in figures 10, 11, and 12.

FIGURE 9.—Textural features and hydrologic properties of the dominant unweathered sediments in the ground-water reservoir of the Friant–Kern Canal service area. (After unpub. data by I. E. Klein, U.S. Bur. Reclamation, 1954.)



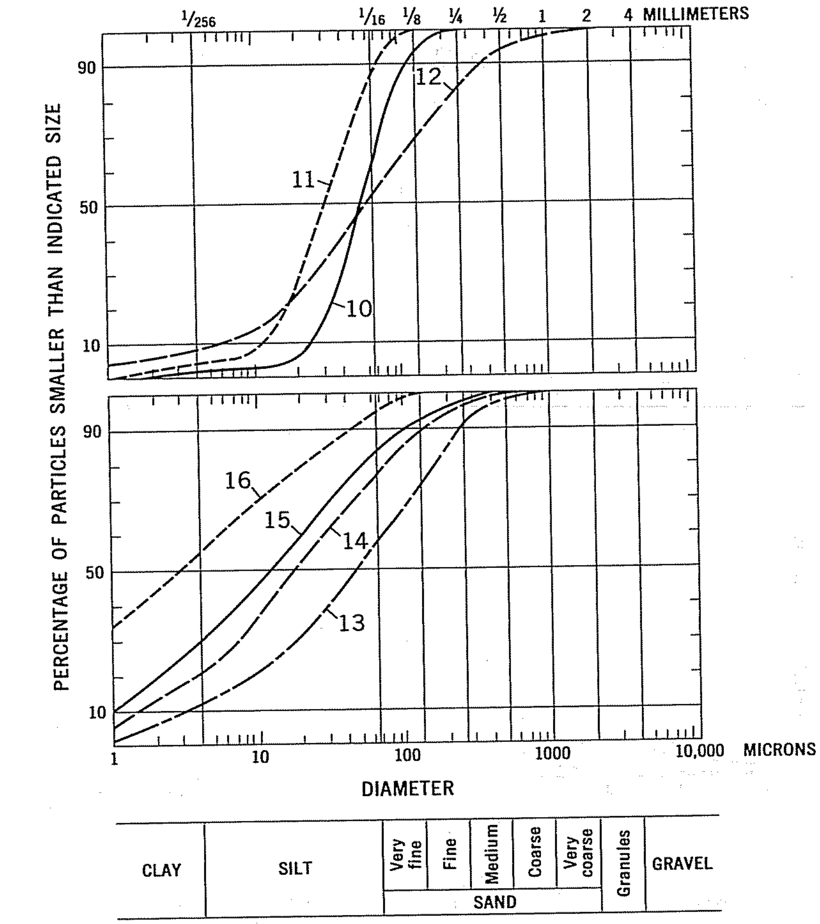
Reference No.	U.S. Bur. Reclamation test hole	Depth (ft)	Textural classification (based on average size and sorting)	Effective size (D_{10})	Median size (D_{50})	10 percent maximum size (D_{90})	Decile sorting factor $\sqrt{\frac{D_{90}}{D_{10}}}$	Porosity (volume percent)	Specific yield (or effective porosity) (volume percent)	Permeability coefficient (U.S. Geol. Survey) (gpd sq ft)
				Microns						
1	20/23-8D	418.0	Well-sorted coarse sand	125	600	1,800	3.8	39.3	34	460
2	27/25-1A	401.5	Ill-sorted coarse sand	74	690	2,300	5.7	38.0	28	85
3	28/24-23	364.3	Well-sorted medium sand	125	340	720	2.4	39.7	30	130
4	25/26-16C	482.3	Ill-sorted medium sand	28	320	1,190	6.5	32.0	22	30

FIGURE 10.—Mechanical-analysis data and hydrologic properties of four representative coarse and medium sands in the ground-water reservoir of the Friant–Kern Canal service area. (After unpub. data by I. E. Klein, U.S. Bur. Reclamation, 1954; table abstracted from regional laboratory reports on the core samples from the test holes represented.)



Reference No.	U.S. Bur. Reclamation test hole	Depth (ft)	Textural classification (based on average size and sorting)	Effective size (D_{10})	Median diameter (D_{50})	10 percent maximum size (D_{90})	Decile sorting factor $\left(\sqrt{\frac{D_{90}}{D_{10}}}\right)$	Porosity (volume percent)	Specific yield (or effective porosity) (volume percent)	Permeability coefficient (U.S. Geol. Survey) (gpd sq ft)
				Microns						
5	20/23-8D	593.0	Well-sorted fine sand	90	210	430	2.2	41.2	33	150
6	23/25-9D	94.0	Very ill sorted silty sand	5	180	1,000	14.1	32.1	10	.2
7	31/25-27	399.0	Well-sorted fine sand	45	120	240	2.3	40.4	34	47
8	20/23-8D	546.0	Very ill sorted silty sand	4	100	570	11.9	32.8	6	.2
9	20/23-8D	686.5	Ill-sorted fine sand	7	110	370	7.3	35.9	17	.2

FIGURE 11.—Mechanical-analysis data and hydrologic properties of five representative fine sands and silty sands in the ground-water reservoir of the Friant–Kern Canal service area. (After unpub. data by I. E. Klein, U.S. Bur. Reclamation, 1954; table abstracted from regional laboratory reports on the core samples from the test holes represented.)



Reference No.	U.S. Bur. Reclamation test hole	Depth (ft)	Textural classification (based on average size and sorting)	Effective size (D_{10}) (Microns)	Median diameter (D_{50}) (Microns)	10 percent maximum size (D_{90}) (Microns)	Decile sorting factor $\left(\sqrt{\frac{D_{90}}{D_{10}}}\right)$	Porosity (volume percent)	Specific yield (or effective porosity) (volume percent)	Permeability coefficient (U.S. Geol. Survey) (gpd per sq ft)
10	23/23-33A	733.2	Well-sorted silt	22	50	110	2.2	40.5	28	9
11	23/23-33A	233.5	Well-sorted silt	10	30	70	2.7	40.6	17	.2
12	20/23-8D	241.5	Ill-sorted silt	4	58	350	9.4	36.0	7	.07
13	25/23-28	93.5	Ill-sorted silt	3	40	250	9.1	33.2	2	.02
14	28/22-9B	597.5	Clayey sandy silt	*1	18	140	*12	36.7	<½	.007
15	23/23-33A	219.5	Silty clay	*1	13	120	*11	38.5	<½	.003
16	23/23-33A	155.6	Clay	*¼	3	40	*20	47.0	<½	†<.001

*Calculated.
†Estimated.

FIGURE 12.—Mechanical-analysis data and hydrologic properties of seven representative silts and clays in the ground-water reservoir of the Friant–Kern Canal service area. (After unpub. data by I. E. Klein, U.S. Bur. Reclamation, 1954; table abstracted from regional laboratory reports on the core samples from the test holes represented.)

ful and to reasonably represent the physical situation under the stated assumptions.

California Water Resources Board, 1956, Geology and ground water of Ventura County, California: California Water Resources Board, Ventura County Inv., Bull. 12, v. 2, app. B, p. 40–41.

In its South Coastal Basin Investigation, the Division of Water Resources conducted extensive field and laboratory investigations for the purpose of assigning specific yield values to various types of material appearing in well logs. These procedures are described in Bulletin No. 45, "Geology and Ground Water Storage Capacity of Valley Fill" (Division of Water Resources, 1934). With slight variations, the values determined in this earlier work and Bulletin 46, "Ventura County Investigation" were adopted for compiling the change of storage estimates presented here.

The task of assigning specific yield values to the sediments appearing in logs was simplified by dividing all basin sediments into eight general categories. These included soil, clay, clay-sand, clay-gravel, tight sand, sand, tight gravel, and gravel. Sand, gravel, and clay, which constitute the bulk of the basin sediments, were generally found to be well differentiated on the drillers' logs. Combinations of these materials, however, were frequently described by such unique terms as "ooze," "muck," "cement," etc. Materials so described were placed, based on the judgment of a geologist, into one of the above eight categories. Table 13 indicates specific yield values assigned to the general categories. In certain instances, these values were altered slightly whenever field observations indicated the advisability of changes.

TABLE 13.—*Specific yields of sediments in Ventura County, Calif.*

Material	*Specific yield (percent)*
Soil, including silty clay	3
Clay, including adobe and hardpan	0
Clayey sand, including sandy silt	5
Clayey gravel	7
Sand	25
Tight sand, including cemented sand	18
Gravel, including gravel and sand	21
Tight gravel, including cemented gravel	14

Back, William, 1957, Geology and ground-water features of the Smith River plain, Del Norte County, California: U.S. Geol. Survey Water-Supply Paper 1254, p. 43–45.

Specific yields assigned to deposits on the Smith River plain were modified from specific-yield values used in a report on the Sacramento Valley (Poland, Davis, Olmsted, and Kunkel, 1951). * * * Table 14 shows the specific yields, in percent, used to estimate ground-water storage for the Smith River plain.

TABLE 14.—*Specific-yield values for the various lithologic materials used in estimating ground-water storage on the Smith River plain, California*

	Specific yield (percent)
Class 1: Gravel; boulders; sand and gravel	25
Class 2: Dune sand	15
Class 3: Sand; clay and sand; fine sand	10
Class 4: Clay and gravel; sandy clay	5
Class 5: Clay; blue shale	1

For each unit, * * * the drillers' logs were examined and the thickness of each class of material between 10 and 35 feet below the land surface was totaled. The total thickness for each class was divided by the total thickness for all classes to determine the percentage represented by each class. Each percentage was multiplied by the specific-yield value for that class; then these products were totaled and divided by 100 to determine the average specific yield for the sediments in that storage unit.

California Water Rights Board, 1957, Determination of specific yield and storage capacity: California Water Rights Board Spec. Rept. 2 of Referee Tia Juana Basin, app. C., p. C12–C23.

In order to apply values of specific yield to materials described in drillers' logs, it was necessary to establish values that could be correlated with these descriptions. The primary bases for classification of materials in available drillers' logs being dominant or median grain sizes. In order to provide such a comparison the relationship between the maximum ten percent grade size and dominant grain size was determined from cored samples. This relationship is depicted on figure 13, which indicates that the maximum ten percent grade size is in general one grade size larger than the dominant particle size.

Many of the sediments reported in drillers' logs are broadly classified, necessitating the application of average specific yields to the large portion of the sediments so classified in the basin. Correlation of specific yields of cored samples with the general classification of that material shown by existing well logs in the test hole vicinity indicates a range of 17 to 32 percent specific yield for "sand" as described by the driller. Because of this variation average values of specific yields were applied to such general classification of sediments. Values so used are listed in table 15.

* * * * * * *

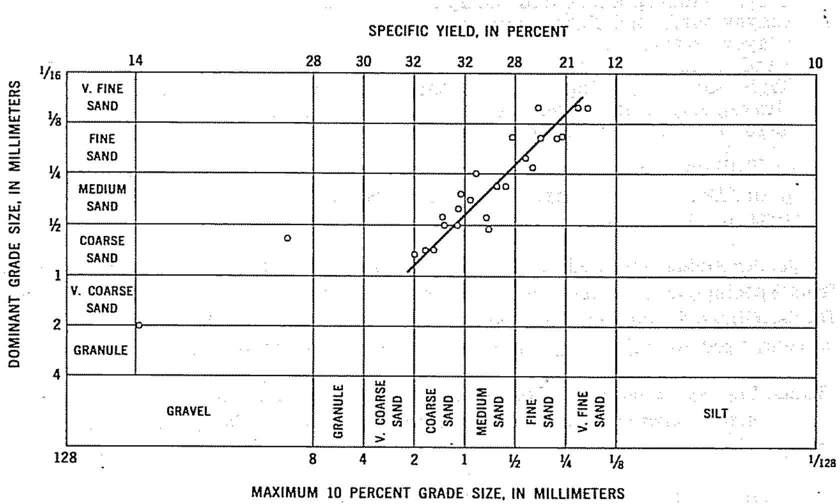


FIGURE 13.—Grade-size distribution of cored samples from the Tia Juana Basin, Calif. (After California Water Rights Board, 1957.)

Determination of specific yield of valley fill materials in type (2) samples [3-inch inside diameter by 3 feet long] was accomplished by use of the laboratory drainage method. * * *.

* * * * * * *

After saturation the samples were immediately weighed and placed in a moisture room, in which atmospheric temperature and humidity remained essentially constant, and allowed to drain freely. The temperature of the air was maintained at 70 degrees Fahrenheit and the relative humidity at approximately 100 percent. * * *.

Initial effluent was determined by weighing the samples daily for a period of twenty days; water loss thereafter was determined weekly. * * *.

After the samples had drained 34 or 35 days, at which time the remaining moisture content consisted essentially of moisture held as specific retention and capillary water, the samples were inadvertently subjected to ambient atmospheric temperature and humidity until 134 days of draining time had elapsed. * * *.

* * * * * * *

The values of specific retention and specific yield obtained from laboratory drainage of type (2) samples * * * are illustrated graphically on figure 14. Individual computed values * * * are represented by the average curve shown as a dashed line labeled Specific Yield–Partial Saturation on figure 14 and values incorporating porosity are shown by the solid line labeled Specific Yield-Total Saturation. The latter values are believed more representative and were therefore utilized. Thus specific yields for materials contained in type (2) samples were taken as the difference between porosity and specific retention. A comparison of the specific yield values so determined for Tia Juana Basin sediments and the specific yields of South Coastal Basin sediments are shown on figure 15, where these values are both depicted in relation to grain size.

Although the origin and mode of deposition of sediments in Tia Juana and South Coastal Basins differ, the specific yields of sediments sampled in Tia Juana Basin were found to be only slightly higher than those in the South Coastal Basin. The greatest variation (2½ percent specific yield) occurred in fine and medium sand, with less variation (1 percent specific yield) in the very fine and coarse sands. Figure 15 also illustrates the size distribution of Tia Juana Basin sediments based upon the average percentages of the various grain sizes found in 32 samples obtained from five test holes.

Specific yield values determined by the drainage method for Tia Juana Basin sediments varying from fine to coarse sand indicate an average of 1.9 percent (specific yield) greater value than the South Coastal Basin sediments. In view of the small variation in corresponding yield values and the more extensive studies of South Coastal Basin sediments, the specific yield values based upon maximum ten percent grade size are considered valid for the problem under consideration and therefore have been adopted.

* * * * * * *

The greatest single factor contributing to error in computing storage capacity is the well drillers' interpretation of the material he encountered during well drilling and descriptions have been found to vary widely among drillers when describing similar sediments. A tendency exists among drillers to describe sediments on the basis of their permeability rather than water-yielding capacity. Therefore, the problem for the investigator is to differentiate between the well logs and consider only the more reliable logs when assigning yield values, although the less reliable logs are often of a qualitative value. For these reasons,

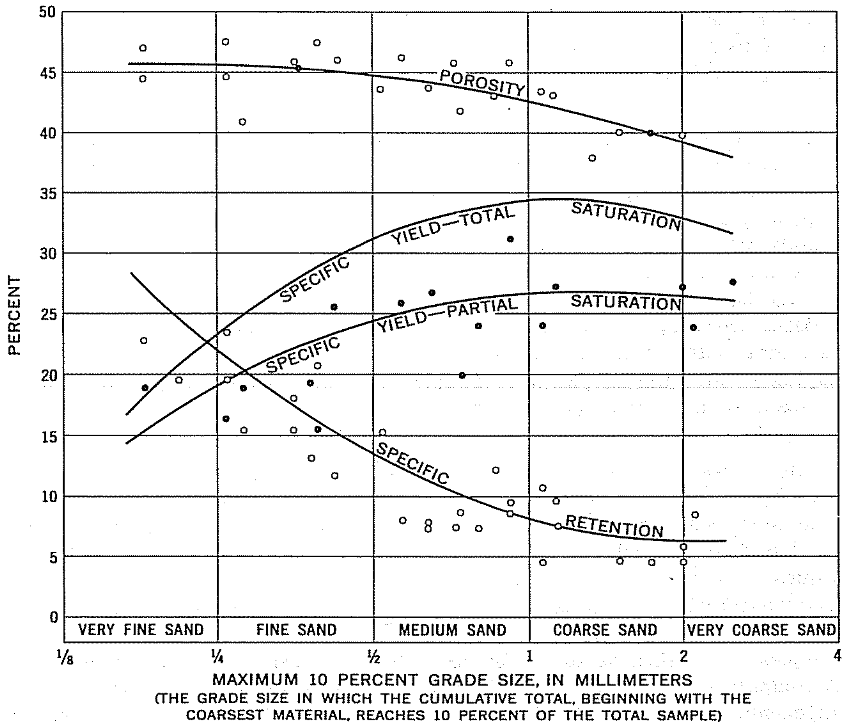


FIGURE 14.—Porosity, specific yield, and specific retention of sediments from the Tia Juana Basin, Calif. (After California Water Rights Board, 1957.)

all drilling logs have been classified broadly into two categories—differentiated and undifferentiated. Sample test holes, test pit samples, test wells, and water wells that have good material descriptions are classified as differentiated, with the remaining sources of information called undifferentiated. Specific yield values assigned to the various types of materials in differentiated and undifferentiated well logs are listed in table 15. The values assigned to materials described in undifferentiated logs generally fall into the category of clay, sand or gravel.

TABLE 15.—*Specific yield of water-bearing sediments in Tia Juana Basin, Calif.*

Differentiated description of material	*Average specific yield (percent)* [1]	*Undifferentiated description of material* [2]	*Average specific yield value used (percent)*
Clay	1	Clay	1
Sandy clay	5	Sandy clay	5
Silt	10	Silt	10
Very fine sand	17	Fine sand	21
Fine sand	25		
Medium sand	30		
Coarse sand	32	Sand	30
Very coarse sand	31		
Gravelly sand	28		
Fine gravel	26		
Medium gravel	23	Gravel	22
Coarse gravel	18		
Very coarse gravel and boulders	14	Boulders	14

[1] Determined from maximum 10 percent grade size of cored samples.
[2] As contained in drillers' logs.

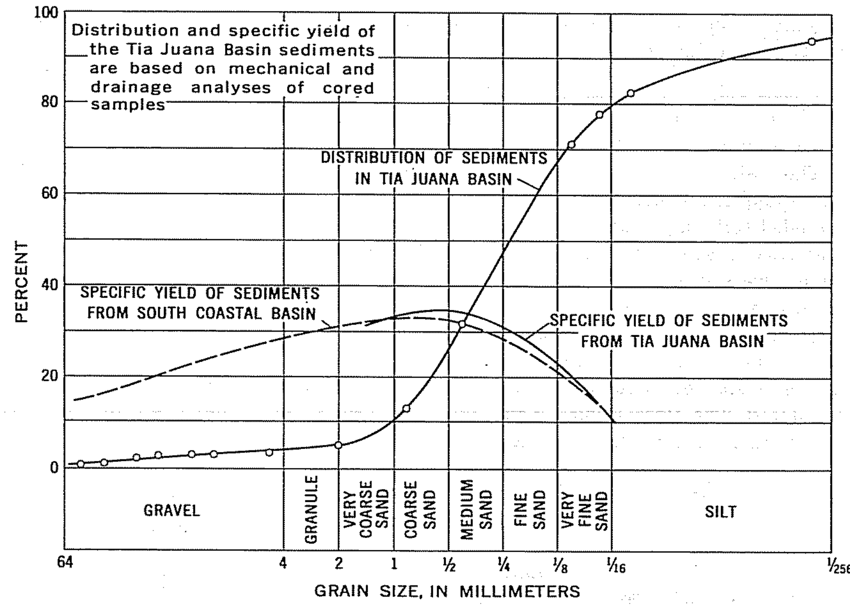


FIGURE 15.—Distribution and specific yield of sediments from the Tia Juana Basin, Calif. (After California Water Rights Board, 1957.)

Values assigned to these materials are averages of the values assigned to differentiated sources of information.

In addition, to estimates of specific yield obtained from sample test holes and wells, several other sources of information have been utilized. During March 1948, tests were conducted at wells owned by the San Ysidro Irrigation District and during September, 1949, at the South Basin plant of the California Water and Telephone Company for a determination of permeability by the discharging well method. Values of specific yield have been determined from data collected during these tests. The San Ysidro test revealed the affected water-bearing materials to have a specific yield of 31 percent which compares in magnitude to the estimated average specific yield of 25 percent for the subarea in which the test was performed. The South Basin test indicated shallow materials to have a yield of 20 percent within the subarea which has an estimated average specific yield of 21 percent, average values being determined from the specific yield map. * * *.

California Water Resources Board, 1958, Geology and ground water of San Luis Obispo County, California: California Water Resources Board, San Luis Obispo County Inv., app. B, p. 26–27.

The changes in ground water storage occurring over selected periods of study were generally not estimated due to lack of historical data on ground water level fluctuations. A certain portion of the total storage can be considered usable storage capacity, but this amount is uncertain in most basins due to lack of data. In general, the estimating procedures required: (1) A determination of total volume of saturated sediments and, (2) an estimate of the percentage of this volume that contained extractable ground water. The first item was obtained by computing the volume of sediments that lay between the water table and the bottom of the basin. The second item was obtained by evaluating the average weighted specific yield of the sediments by analysis of available well logs.

* * * * * * *

With slight variations, the values determined in this [Eckis, 1934] earlier work were adopted for computing the change of storage estimates presented here.

The task of assigning specific yield values to the sediments appearing in logs was simplified by dividing all basin sediments into eight general categories. These included soil, clay, clay and sand, clay and gravel, tight sand, sand, tight gravel, and gravel. Sand, gravel, and clay, which constitute the bulk of the basin sediments, were generally found to be well differentiated on the drillers' logs. Combinations of these materials, however, were frequently described by such unique terms as "ooze," "muck," "cement," etc. Materials so described were placed, based on the judgment of a geologist, into one of the above eight categories. Table 16 indicates specific yield values assigned to the general categories of material encountered. The Paso Robles formation is generally more compacted and weathered than the alluvium and some specific yields were lowered accordingly.

TABLE 16.—*Specific yield of water-bearing sediments in San Luis Obispo County, Calif.*

Material	Specific yield (percent) Alluvium	Paso Robles formation
Soil, including silty clay	5	5
Clay, including adobe and hardpan	3	3
Clay and sand, including sandy silt	5	5
Clay and gravel	7	7
Sand	25	20
Tight sand, including cemented sand	18	15
Gravel, including gravel and sand	21	18
Tight gravel, including cemented gravel	14	13

Davis, G. H., Green, J. H., Olmsted, F. H., and Brown, D. W., 1959, Groundwater conditions and storage capacity in the San Joaquin Valley, California: U.S. Geol. Survey Water-Supply Paper 1469, p. 206–210.

The values chosen for specific yield were based largely on previous work by other investigators in California, with certain rational modifications to fit conditions in the San Joaquin Valley. * * *.

* * * * * * *

The results obtained by Eckis (1934), by Piper and others (1939), by the Sacramento laboratory of the Bureau of Reclamation, and by other less detailed studies were modified somewhat for use in the San Joaquin Valley, and the specific yields listed in table 17 were assigned to the five major groups of material classified in the well logs.

The grouping of drillers' terms and the specific yield of one category—S (sand)—were different from those used by the Geological Survey in the Sacramento Valley investigation (Poland and others, 1951, p. 625), * * *. The specific yield of 25 percent assigned to the coarse gravelly deposits was approximately a general average of the results * * * which ranged from 13 to 35 percent. Probably much of the clean gravel and well-sorted sand near the apexes of the alluvial fans of the east-side streams in the San Joaquin Valley has a specfic yield substantially above 25 percent, as suggested by the Bureau of Reclamation data * * *. However, the writers believe that figure to be a reasonable and conservative estimate of the valleywide average.

Sand and gravel (mixed) was included in the gravel category instead of being grouped with sand as in the Sacramento Valley storage estimate. (See Poland and others, 1951.) Inasmuch as both the G and the S categories were assigned a specific yield of 25 percent in the San Joaquin Valley estimate, it would have made no difference in which category the sand and gravel was placed in computing weighted-average specific yields. However, for geologic interpretations of the data * * * grouping mixed sand and gravel with gravel was more useful and instructive.

TABLE 17.—*Specific yield of water-bearing sediments in the San Joaquin Valley, Calif.*

Group	Material	Specific yield (percent)
G	Gravel; sand and gravel; and related coarse gravelly deposits	25
S	Sand, medium- to coarse-grained, loose, and well-sorted	25
F	Fine sand; tight sand; tight gravel; and related deposits	10
Cg	Silt; gravelly clay; sandy clay; sandstone, conglomerate; and related deposits	5
C	Clay and related very fine grained deposits	3
X	Crystalline bedrock (fresh)	0

DRILLERS' TERMS USED IN ESTIMATING SPECIFIC YIELD

Group G: Gravel, sand and gravel, and similar materials

(Specific yield 25 percent)

Boulders
Coarse gravel
Cobbles
Cobble stones
Dry gravel (if above water table)
Float rocks
Gravel
Loose gravel
Rocks
Water gravel
Gravel and sand
Gravel and sandrock
Rock and gravel
Sand and boulders
Sand and cobbles
Sand and fine gravel
Sand and gravel
Sandy gravel

Group S: Sand

(Specific yield 25 percent)

Coarse sand
Free sand
Loose sand
Medium sand
Running sand
Sand
Sand, water

Group F: Fine sand, tight sand, tight gravel, and similar materials

(Specific yield 10 percent)

Sand and clay
Sand and clay strata (traces)
Sand and dirt
Sand and hardpan
Sand and hard sand
Sand and lava
Sand and pack sand
Sand and sandy clay

TABLE 17.—*Specific yield of water-bearing sediments in the San Joaquin Valley, Calif.*—Continued

DRILLERS' TERMS USED IN ESTIMATING SPECIFIC YIELD—Continued

Group F: Fine sand, tight sand, tight gravel, and similar materials—Continued

(Specific yield 10 percent)

Sand and soapstone
Sand and soil
Sand and some clay
Sand, clay, and water
Sand crust
Sand—little water
Sand, mud, and water
Sand (some water)
Sand streaks, balance clay
Sand, streaks of clay
Sand with cemented streaks
Sand with thin streaks of clay

Coarse, and sandy
Loose sandy clay
Medium sandy
Sandy
Sandy and sandy clay
Sandy clay, sand, and clay
Sandy clay—water bearing
Sandy clay with streaks of sand
Sandy formation
Sandy muck
Sandy sediment
Very sandy clay

Cloggy sand
Coarse pack sand
Compacted sand and silt
Dead sand
Dirty sand
Fine pack sand
Fine quicksand with alkali streaks
Fine sand
Fine sand, loose
Hard pack sand
Hard sand
Hard sand and streaks of sandy clay
Hard sand rock and some water sand
Hard sand, soft streaks

Loamy fine sand
Medium muddy sand
Milk sand
More or less sand
Muddy sand
Pack sand

Poor water sand
Powder sand
Pumice sand
Quicksand
Sand, mucky or dirty
Set sand
Silty sand
Sloppy sand
Sticky sand
Streaks fine and coarse sand
Surface sand and clay
Tight sand

Boulders, cemented sand
Cement, gravel, sand, and rocks
Clay and gravel, water bearing
Clay and rock, some loose rock
Clay, sand, and gravel
Clay, silt, sand, and gravel
Conglomerate, gravel, and boulders
Conglomerate, sticky clay, sand and gravel
Dirty gravel
Fine gravel, hard
Gravel and hardpan strata
Gravel, cemented sand
Gravel with streaks of clay
Hard gravel
Hard sand and gravel
Packed gravel
Packed sand and gravel
Quicksand and cobbles
Rock sand and clay
Sand and gravel, cemented streaks
Sand and silt, many gravel
Sand, clay, streaks of gravel
Sandy clay and gravel
Set gravel
Silty sand and gravel (cobbles)

Tight gravel
Sandy loam
Sandy loam, sand, and clay
Sandy silt
Sandy soil
Surface and fine sand

TABLE 17.—*Specific yield of water-bearing sediments in the San Joaquin Valley, Calif.*—Continued

DRILLERS' TERMS USED IN ESTIMATING SPECIFIC YIELD—Continued

Group F: Fine sand, tight sand, tight gravel, and similar materials—Continued

(Specific yield 10 percent)

Brittle clay and sand
Clay and sand
Clay, sand, and water
Clay, with sand
Clay with sand streaks
More or less clay, hard sand and boulders
Mud and sand
Mud, sand, and water
Sand and mud with chunks of clay
Silt and fine sand

Silt and sand
Soil, sand, and clay
Topsoil and light sand
Water sand sprinkled with clay

Float rock (stone)
Laminated
Pumice
Seep water
Soft sandstone
Strong seepage

Group Cg: Clay and gravel, sandy clay, and similar materials

(Specific yield 5 percent)

Cemented gravel (cobbles)
Cemented gravel and clay
Cemented gravel, hard
Cement and rocks (cobbles)
Clay and gravel (rock)
Clay and boulders (cobbles)
Clay, pack sand, and gravel
Cobbles in clay
Conglomerate
Dry gravel (below water table)

Gravel and clay
Gravel (cement)
Gravel and sandy clay
Gravel and tough shale
Gravelly clay
Rocks in clay
Rotten cement
Rotten concrete mixture
Sandstone and float rock
Silt and gravel
Soil and boulders

Cemented sand
Cemented sand and clay
Clay sand
Dry hard packed sand
Dry sand (below water table)
Dry sand and dirt
Fine muddy sand
Fine sand, streaks of clay
Fine tight muddy sand

Hard packed sand, streaks of clay
Hard sand and clay
Hard set sand and clay
Muddy sand and clay
Packed sand and clay
Packed sand and shale
Sand and clay mix
Sand and tough shale
Sand rock
Sandstone
Sandstone and lava
Set sand and clay
Set sand, streaks of clay
Sticky sand and clay
Tight muddy sand
Very fine tight muddy sand

Dry sandy silt
Fine sandy loam
Fine sandy silt
Ground surface
Loam
Loam and clay
Sandy clay loam
Sediment
Silt
Silt and clay
Silty clay loam
Silty loam
Soft loam
Soil
Soil and clay

TABLE 17.—*Specific yield of water-bearing sediments in the San Joaquin Valley, Calif.*—Continued

DRILLERS' TERMS USED IN ESTIMATING SPECIFIC YIELD—Continued

Group Cg: Clay and gravel, sandy clay, and similar materials—Continued

(Specific yield 5 percent)

Soil and mud
Soil and sandy shale
Surface formation

Top hardpan soil
Topsoil
Topsoil and sandy silt
Topsoil—silt

Decomposed hardpan
Hardpan and sandstone
Hardpan and sandy clay
Hardpan and sandy shale
Hardpan and sandy stratas
Hard rock (alluvial)
Sandy hardpan
Semihardpan
Washboard

Cemented sandy clay
Hard sandy clay (tight)
Sandy clay
Sandy clay with small sand streaks, very fine
Sandy shale
Set sandy clay
Silty clay
Soft sandy clay
Clay and fine sand
Clay and pumice streaks

Clay and sandy clay
Clay and silt
Clay, cemented sand
Clay, compact loam and sand
Clay to coarse sand
Clay, streaks of hard packed sand
Clay, streaks of sandy clay
Clay, water
Clay with sandy pocket
Clay with small streaks of sand
Clay with some sand
Clay with streaks of fine sand
Clay with thin streaks of sand
Porphyry clay
Quicksandy clay
Sand—clay
Sand shell
Shale and sand
Solid clay with strata of cemented sand

Ash
Caliche

Chalk
Hard lava formation
Hard pumice
Porphyry
Seepage soft clay
Volcanic ash

Group C: Clay and related materials

(Specific yield 3 percent)

Adobe
Brittle clay
Caving clay
Cement
Cement ledge
Choppy clay
Clay
Clay, occasional rock
Crumbly clay
Cube clay
Decomposed granite
Dirt
Good clay

Gumbo clay
Hard clay
Hardpan (H.P.)
Hardpan shale
Hard shale
Hard shell
Joint clay
Lava
Loose shale
Muck
Mud
Packed clay
Poor clay

TABLE 17.—*Specific yield of water-bearing sediments in the San Joaquin Valley, Calif.*—Continued

DRILLERS' TERMS USED IN ESTIMATING SPECIFIC YIELD—Continued

Group C: Clay and related materials—Continued

(Specific yield 3 percent)

Shale
Shell
Slush
Soapstone
Soapstone float
Soft clay

Squeeze clay

Sticky
Sticky clay
Tiger clay
Tight clay
Tule mud
Variable clay
Volcanic rock

Group X: Crystalline bedrock (fresh)

(Specific yield zero)

Granite
Hard boulders
Hard granite
Hard rock

Graphite and rocks
Rock (if in area of known crystalline rocks)

The S (sand) category was assigned a specific yield of 25 percent instead of the 20 percent used in the Sacramento Valley study. The Bureau of Reclamation laboratory data * * * indicate that 20 percent probably is much too conservative an estimate for the San Joaquin Valley, even allowing for the fact that many well drillers do not discriminate between tight or silty sands and relatively loose, well-sorted sands. Moreover, as the data of Eckis and Gross indicate * * * many sands have higher specific yield than gravels, owing to the higher porosity of the sands. In many places, as for example in the south coastal basin of southern California where Eckis and Gross conducted their study, most gravelly beds are much less well sorted than the sands; hence, their porosity and specific yield are lower. Accordingly, in the San Joaquin Valley sand was assigned the same specific yield as gravel. * * *.

Tight sand, tight gravel, fine sand, and many similar terms suggesting restricted permeability and drainable void space were placed in an intermediate category having an assigned specific yield of 10 percent. Several types included here were assigned a specific yield of only 5 percent in the Sacramento Valley study (Poland and others, 1951) but the writers believe that the present grouping, which is supported by laboratory-test data of the Bureau of Reclamation, is more logical.

A fourth category comprising gravelly clay, sandy clay, sandstone, conglomerate, and related very poorly sorted or tightly cemented materials of low premeability was given a specific yield of 5 percent. This value is about the same as that obtained by Eckis and Gross for clayey weathered subsurface materials in the south coastal basin and is slightly higher than the average of 4 percent obtained by Piper for very fine sand, silt, and clay. Although a specific yield of 5 percent may be too high for true silty clay, clayey silt, and sandy clay, * * * such materials have higher specific yields than the "clay" described by drillers, and these materials accordingly were placed in the 5-

percent category. However, where Bureau of Reclamation geologists rather than well drillers described these materials, they were assigned a specific yield of only 3 percent.

The finest grained deposits, mostly described as some type of "clay" were assigned a specific yield of 3 percent. This specific yield is higher than that used for clay in the south coastal basin study, but is midway between the values used for clay and sandy clay in the unweathered subsurface alluvial deposits in that area. The term "clay" as applied by the driller, is likely to include many beds that are silty or sandy, if they contain much material so fine that it remains in suspension in the drilling fluid. Comparisons of sample descriptions by well drillers and Bureau of Reclamation geologists indicated that some of the materials classified by the drillers as "clay" were described by the geologists as silt or even fine sand.

Evenson, R. E., 1959, Geology and ground-water features of the Eureka area, Humboldt County, California: U.S. Geol. Survey Water-Supply Paper 1470, p. 35.

The deposits for which estimates of storage capacity are considered are the alluvium, channel deposits, and the lower terrace deposits of the Eel, Van Duzen, and Mad Rivers. The following specific-yield values, table 18, assigned to these deposits encountered in wells in the Eureka area, have been adapted with slight modification from those figures used in estimating the ground-water storage capacity of similar deposits in the Sacramento Valley (Poland and others, 1951).

* * * * * * *

Most of the material penetrated by shallow wells in the alluvial deposits along the Eel, Van Duzen, and Mad Rivers consists of fine- to coarse-grained sand and gravel and a few thin streaks of silt or clay—ordinarily not thick enough to be noted on well logs. * * *

TABLE 18.—*Specific yields for the alluvial deposits of the Eel, Van Duzen, and Mad Rivers, Humboldt County, Calif.*

Material	*Specific yield (percent)*
Gravel	25
Sand and gravel, sand	20
Sand and silt	15
Sand and clay, soil and clay, gravel and clay	10
Clay	3

Rasmussen, W. C., and Andreasen, G. E., 1959, Hydrologic budget of the Beaverdam Creek basin, Maryland: U.S. Geol. Survey Water-Supply Paper 1472, p. 83–92.

The ratio of the volume of drained, or gravity, water to the total volume of the rock or soil is called the specific yield * * *. The amount of water that saturated sediments will yield to gravity is equal to ΔHY, where ΔH is the change in ground-water stage and Y is the specific yield.

The same expression represents ideally the amount of water entering storage with a rising water level. However, in a sand that is fairly homogeneous except that a silt or few clay lenses are within the zone of ground-water fluctuation, a rise of the water table from below to above one of these lenses would not result immediately in complete saturation of it. Though the silt or clay might be considerably more porous than the surrounding sand, its permeability might be so low that a rather long time would be required for the water to penetrate the lens, and even then some air would be trapped. Conversely, when the water table receded, leaving a partly or completely saturated silt-clay lens somewhere within the capillary fringe, the lens would not yield its gravity water as readily as the surrounding sand. Rather there would be a leakage from the silt-clay lens down to the lowered water table. Further, the water table responds quickly to every sizable rainfall, and a rapidly rising water table entraps air in even the coarser sediments. Trapping of air results in a decrease in porosity and permeability, until the air is dissolved in the water.

Because of these considerations, a new term, gravity yield, will be defined here in such a way that the definition will include length of drainage time. The gravity yield of a rock or soil after saturation or partial saturation is the ratio of (1) the volume of water it will yield by gravity to (2) its own volume, during the period of ground-water recession. Gravity yield, in effect is a "field" specific yield; it is a function of time and of previous fluctuations of infiltering water, as well as of the character of the rock or soil, * * *.

* * * * * * *

The * * * estimates of gravity yield, which range from 8.7 to 13.0 percent, average 11.1 percent [table 19] * * *. These check values of gravity yield were obtained under conditions of a rising water table, when the gravity yield percentage would be lower because of entrapped air. That is, the water levels would be too high, and the gravity yield thus would be computed too low. Hydrologists have noted the same phenomenon in the dunes of the Netherlands. Krul and Liefrinck (1946, p. 40) say: "An observation worth mentioning was that indications of water levels computed during an infiltration period with a rising water table were always found to be too high, a phenomenon which was attributed to compression of the air contained in the sand interstices * * *."

* * * * * * *

TABLE 19.—*Specific yield of sediments from Beaverdam Creek basin, Maryland*

Material	*Specific yield (percent)*
Medium sand	25
Sandy clay	11

Porosity determinations for sediments from the Beaverdam Creek basin were * * *:

Type of material	*Porosity (percent)*
Medium-grained sand	38.0
Sandy silt	38.3
Sandy clay	36.5
Average	37.6

* * * * * * *

The converted moisture equivalents, which range from 2.3 to 39.6 percent, are greatest for the clay and least for the sand. * * * The pit logs * * * indicate a predominance of sand, so that a single arithmetic average of the converted moisture equivalents, assumed to be equal to the specific retention, is reasonable. Substituting the average porosity and the average converted moisture equivalent in equation (6) gives a specific yield of 21.0 percent (37.6–16.6).

It is possible that this high specific yield was due, in part, to inadequate sampling of the basin. Serious errors are apt to be brought in when comparatively large areas are represented by only a few samples. It is reasonable, however, that the specific yield would be higher than the gravity yield, because it is unlikely that ground-water drainage during the period of observation was ever accomplished so completely that all gravity water was released from storage.

Wilson, H. D., Jr., 1959, Ground-water appraisal of Santa Ynez River basin, Santa Barbara County, California, 1945–52: U.S. Geol. Survey Water-Supply Paper 1467, p. 24–25.

Laboratory methods are subject to the usual errors inherent in any method involving sampling. Also, for the preliminary estimate it was not believed justified to sample the alluvial deposits in great detail. Pumping-test methods are of doubtful value in obtaining specific-yield values for the alluvial deposits of the Santa Ynez River basin because field conditions are far different from the ideal conditions which must be assumed in the derivation of the equations expressing pumping test theory * * *.

For the preliminary estimates of this report, specific yield was approximated by estimating the proportion of different classes of material as reported in the available well logs and assigning arbitrary specific-yield values to each class [table 20]. * * * The arbitrary specific-yield values selected for different classes of material as reported in the well logs were determined by comparison with other areas similar to the Santa Ynez River basin in which specific-yield values had been obtained from field and laboratory tests. The method is based in part on mechanical analysis of the material and was used rather successfully by Eckis (1934) in the south coastal basin of southern California. * * * In the Mokelumne area, California, estimates of specific yield by both the volumetric method and the drainage method were made by Piper and others (1939, p. 120–121). * * *.

TABLE 20.—*Specific yield for alluvial deposits of the Santa Ynez River basin, California*

Material	*Specific yield (percent)*
Gravel	25
Sand	30
Fine sand	20
Gravel, cemented or clayey	10
Silt	5
Clay	5

The materials in the Santa Ynez River basin are roughly comparable to those in the south coastal basin. Accordingly, a specific-yield value of 25 percent was assigned to gravel, 30 percent to sand, 20 percent to fine sand, 10 percent to cemented or clayey gravel, and 5 percent to silt and clay. The deposits found in the south coastal basin are mostly in alluvial fans, whereas the deposits of the Santa Ynez are river-channel and flood-plain deposits in which the gravel is better sorted and contains less fine material. Possibly, therefore, the gravel has a slightly higher specific yield than 25 percent. Conversely, coarse gravel, such as in the alluvium of the Santa Ynez River, contains an assortment of large pebbles, cobbles, and boulders that have no specific yield and fill considerable space, tending to lower the specific yield of the material as a whole. For this reason the lower value, close to that used by Eckis, was considered more appropriate for this area than Piper's value of 35 percent for gravel and coarse sand.

Kunkel, Fred, and Upson, J. E., 1960, Geology and ground water in Napa and Sonoma Valleys, Napa and Sonoma Counties, California: U.S. Geol. Survey Water-Supply Paper 1495, p. 64–65, 78–79.

Specific yield.—Estimates of specific yield were made by classifying the materials in the younger and older alluvium, as reported in drillers' logs, into groups, and assigning a specific-yield value to the material in each group. In the drillers' logs, gravel, sand, clay, and volcanic rocks are usually identified. The more complete logs mention the color, coarseness of grain, hardness, degree of cementation, and other characteristics readily related to the formations or lithologic types. The drillers' terms were grouped into five general classes of material of similar water-bearing properties * * * [table 21].

TABLE 21.—*Specific yields for alluvium in Napa and Sonoma Valleys, Calif.*

Napa Valley	*Specific yield (percent)*
Gravel, boulders, gravel and boulders	25
Sand; sand and boulders; sand and gravel; sand, gravel, and boulders; water	20
Clay and gravel alternating; clay, gravel, and water; clay and sand; clay, sand, and gravel; clay and gravel, sandy; clay, sandy, and boulders; gravel and sandstone; sandy loam; sand, gravel, boulders, and clay mixture; sand, gravel, boulders, and some clay; sand and hard gravel; sand and rock; some water	10
Clay and gravel; cemented conglomerate; cemented gravel; cemented sand, gravel, and clay; cemented sand and boulders; clay and boulders; clay, gravel, no water; clay and gravel; clay with gravel; clay and rock; sandy clay; clay with sand; gravel, boulders, and clay; hard gravel (cementing assumed); dry gravel (cementing assumed); hardpan and boulders; loam; dry sand (cementing assumed); sandrock; sandstone	5
Clay; clay and soil; hardpan; hardpan and clay; broken rocks; rocks; rock(s), water; soil; surface; tule mud	3
Sonoma Valley	
Gravel, boulders, gravel and boulders	25
Sand; sand and boulders; sand and gravel; sand, gravel, and boulders; water	20
Clay and gravel alternating; clay, gravel, and water; clay and sand; clay, sand, gravel; clay and gravel, sandy; sandy clay, and boulders; gravel and sandstone; sandy loam; sand and clay; sand, gravel, boulders, and clay mixture; sand, gravel, boulders, and some clay; sand and hard gravel; sand and rock; some water; volcanic ash; tuff; pumice; tuff and gravel; tuff and boulders	10
Clay with gravel; cemented conglomerate; cemented gravel; cemented sand, gravel, and clay; cemented sand and boulders; clay and boulders; clay, gravel, no water; clay and gravel; clay with gravel; clay and rock; sandy clay; clay with sand; gravel, boulders, and clay; hard gravel (cementing assumed); dry gravel (cementing assumed); hardpan and boulders, loam and dry sand (cementing assumed); sandrock; sandstone; boulders and red clay; volcanic rocks and rocks (agglomerate)	5
Clay; clay and soil; hardpan; hardpan and clay; broken rocks; rocks; rock(s), water; soil; surface; tule mud; red volcanic rocks; soft rock; red rock; some water; porous rock	3
Rock; hard rock; solid rock; basalt; granite	0

It was not feasible in this investigation to attempt to make field determinations of the specific yield of the different types of water-bearing material. Therefore, an estimated specific-yield value was assigned to each of the five general classes of material on the basis of available data. These values are the same as were applied in the Sacramento Valley investigation (Poland and others, 1951, p. 625) on the basis of the work of Eckis (1934) and Piper and others (1939), and are applied to the same classes of material as nearly as could be determined from the drillers' logs. The names of the materials included in each group are those commonly used and listed by drillers in the area.

* * * * * * *

To determine the average specific yield for each depth zone in each ground-water storage unit, the thickness, in feet, of each class of material in each depth zone was totaled. These thicknesses were converted to percentages of total thickness of all the materials in each zone; and these percentages were multiplied by the specific-yield value assigned to the particular class of material. The sum of these products is the average specific yield for each depth zone. In other words, the various specific yields are prorated according to the relative thickness of the material that has each specific-yield value.

* * * * * * *

Because vertical boundaries are assumed for the ground-water storage units in Sonoma Valley, the volume of each storage unit is equal to the area of the unit multiplied by its thickness. * * * The specific yield of the younger and older alluvium is estimated on the basis of drillers' logs, as for Napa Valley. * * *.

Because the ground-water storage capacity of Sonoma Valley was estimated to a depth of 200 feet, some volcanic material beneath the older alluvium at the edges of the plain was included in the estimate and in the classification of materials. In general, the pumice and tuff are assumed to be comparable in specific yield to sandy clay and gravel, the agglomerate to clay and gravel, and clayey volcanic rocks to clay. The flow rocks yield practically no water; therefore, in Sonoma Valley a sixth class of material, "rock," is added * * * [table 21].

Moulder, E. A., Klug, M. F., Morris, D. A., and Swenson, F. A., 1960, Geology and ground-water resources of the lower Little Bighorn River valley, Big Horn County, Montana: U.S. Geol. Survey Water-Supply Paper 1487, p. 42–43.

The properties of the fine-grained sediments overlying the coarse-grained terrace deposits are important in determining whether the land is irrigable and whether it can be drained. Laboratory tests indicate that the hydrologic properties vary greatly even though the textural properties are similar [table 22]. For example, some samples classified as medium had a lower coefficient of permeability than

TABLE 22.—*Specific yield of unconsolidated materials in the Little Bighorn River valley, Montana*

[Specific yield values rounded to nearest whole number for present report]

Material	*Specific yield (percent)*
Very coarse (predominantly gravel)	25
Coarse (predominantly coarser than very fine sand)	32
Medium (loam, silty loam, and very fine sandy loam)	28
Moderately heavy (clay loam, silty clay loam, and sandy clay loam)	29
Heavy (clay and silty clay)	17

some samples classified as heavy. The specific retention generally proved to be the only property consistent with the particle-size analysis [fig. 16 was prepared by A. I. Johnson to illustrate this relationship], hence, the textural classification apparently is a good measure of the capillary retentiveness of the material and the height of the capillary fringe above the water table. Because of this relationship between capillary and soil texture, soil-classification maps were used in deciding how deep the drains must be to lower the water table sufficiently to alleviate waterlogging.

* * * * * * *

A comparison of specific yields determined by laboratory tests with the storage coefficients determined by field tests suggests that the larger values obtained in the laboratory represent the storage coefficient to be expected after a very long period of draining and that the smaller values obtained from the field tests represent the storage coefficient of the fine-grained sediments during only the short period of the field test. Therefore, the laboratory values are more nearly representative of the effectiveness of drainage measures.

Thomasson, H. G., Jr., Olmsted, F. H., and LeRoux, E. F., 1960, Geology, water resources, and usable ground-water storage capacity of part of Solano County, California: U.S. Geol. Survey Water-Supply Paper 1464, pp. 284–286, 366–368.

The continental sediments examined in the south coastal basin investigation were composed chiefly of alluvial-fan deposits that were laid down by torrential but intermittent streams of steep gradient. In contrast, the near-surface materials underlying most of the Putah area were transported by Putah Creek and the small streams to the south, and were deposited on the broad, relatively flat channel-ridged plain. Accordingly, the alluvial deposits in the south coastal

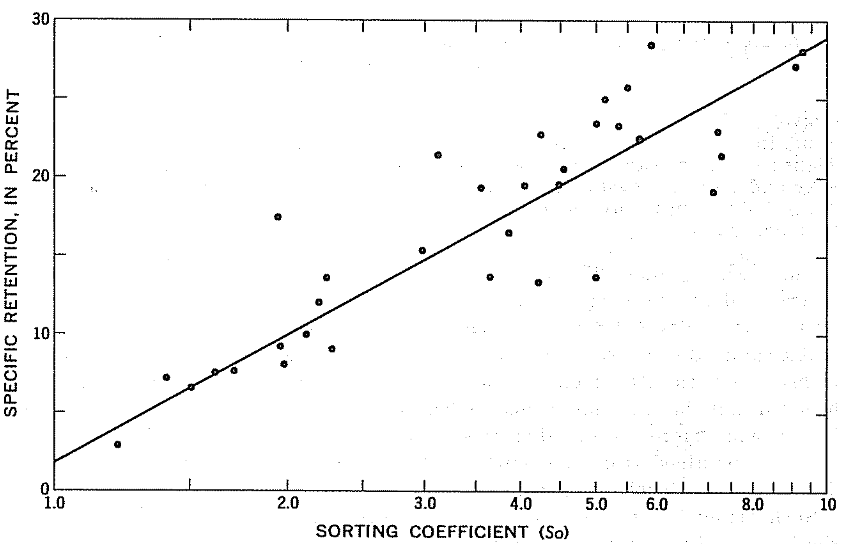


FIGURE 16.—Relation of specific retention to sorting coefficient in alluvium of the Little Bighorn River valley, Montana.

basin undoubtedly are much coarser than those in the Putah area, much of the clay in the south coastal basin being of residual rather than depositional origin.

* * * * * * *

The samples tested in the Mokelumne investigation were obtained at depths of less than 15 feet from unconsolidated sediments of late Pleistocene and Recent age. On the other hand, wells drilled to a depth of 200 feet in the Putah area penetrate the Tehama formation and related continental sediments of Pliocene to early Pleistocene age in their lower portions throughout the area and almost from the land surface in some parts of the area. These older deposits are more weathered and indurated and, group for group as described by drillers, presumably are of lower specific yield than the alluvium. Certainly the yield factors of wells tapping these older deposits in the Putah area are systematically much lower than the yield factors of wells tapping only the Recent and upper Pleistocene alluvial deposits, suggesting a decrease of permeability and probably of specific yield in the older deposits.

The results obtained in those two investigations, together with specific-yield data from less detailed studies by others, were used as a basis from which to assign arbitrary percentages for specific yield of the five general classes of material in the Putah area. However, the figures obtained experimentally in the two detailed investigations were considered to be slightly higher than would be warranted for use in connection with the respective categories of material as classified from local drillers' logs in the Putah area.

Therefore, the percentages obtained in the earlier investigations were modified somewhat for use in the Putah area because of differences in the lithologic and hydrologic character of the sediments, which were considered to reflect differences in the source and composition of the materials and in the conditions under which the alluvial deposition occurred in the different areas. Table 23 shows the specific yield assigned to each of the five categories of material.

* * * * * * *

TABLE 23.—*Specific yield used to estimate total ground-water storage capacity in the Putah area, California*

Material	*Specific yield (percent)*
Gravel	25
Sand, including sand and gravel, and gravel and sand	20
Tight sand, hard sand, fine sand, sandstone, and related deposits	10
Clay and gravel, gravel and clay, cemented gravel, and related deposits	5
"Clay," silt, sandy clay, lava and related fine-grained deposits	3
[Cretaceous rocks	0]

The specific yield of 25 percent assigned to the gravel category was the highest figure used in the computations for the Putah area. This figure was a rough average of results * * * which ranged from 13 to 35 percent.

The sand category was assigned a specific yield of 20 percent, which was appreciably below the 24-percent average of the experimental data. However, it is believed that the material ordinarily logged as sand by drillers in the Putah area is somewhat more consolidated or silty and, hence, of lower specific yield than the sand obtained from the south coastal basin and from the shallow alluvial deposits of the Mokelumne area.

Such drillers' terms as tight sand, hard sand, sandstone, cemented sand, and similar descriptive terms suggesting relatively low permeability and drainable void spaces were mentioned in enough well logs to warrant an intermediate category, to which a specific yield of 10 percent was assigned.

The fourth group comprised material described by means of 21 different terms of drillers, to refer to such materials as clay and gravel, "dry gravel," cemented gravel, and gravelly clay. Although obviously of low permeability and probably low specific yield, these materials doubtless include some moderately permeable beds of fair specific yield, and an average specific yield of 5 percent was assigned.

The finest grained deposits, including clay, silt, sandy clay, hardpan, muck, shale, and lava were assigned a specific yield of 3 percent. Deposits included in this category comprise more than two-thirds of the sediments in the 20- 200-foot zone in the Putah area; only locally do the coarse-grained deposits exceed half the section. The specific yield of 3 percent is higher than that used for clay in the south coastal basin study, but it is midway between the values used for clay and sandy clay in the unweathered subsurface alluvial deposits in that area. The term "clay" as applied by the driller is likely to include many beds that are silty or sandy, if they contain much material so fine that it remains in suspension in the drilling fluid. * * *.

* * * * * *

The total ground-water storage capacity * * * in the Suisun-Fairfield area was estimated by the same method as that used in the Putah area but with a few minor variations * * *.

* * * * * *

As in the Putah area, the average specific yield for each depth range in each storage unit was estimated from the percentages of material * * * and the specific yields in table 23 plus a specific yield of zero for the Cretaceous rocks. The estimates of total storage capacity were then the product of the total volume of each subunit times its estimated average specific yield.

California Department of Water Resources, 1961, Planned utilization of the ground water basins of the coastal plain of Los Angeles County: California Dept. Water Resources Bull. 104, app. A, p. 121, Attachment 2, p. 2–3, 2–4.

Specific yield values for the sedimentary deposits of Los Angeles County are given in table 24. These specific yield values were compiled from available data, including work done by the State Water Rights Board for the San Fernando Valley Reference, and from Bulletin 45 (Calif. D. W. R., 1934). They were also checked against figures obtained from well tests but no new determinations were made during this investigation. Specific yield values are multiplied by the thickness and areal extent of the water-bearing sediments to determine the total storage capacity of these sediments. * * *.

Kazmi, A. H., 1961, Laboratory tests on test drilling samples from Rechna Doab, West Pakistan, and their application to water resources evaluation studies: Athens, Internat. Assoc. Sci. Hydrology Pub. 57, p. 496, 500.

These tests have been used to calculate the specific yield of the samples, using the formulae:

$$\text{Specific retention} = \text{Centrifuge moisture equivalent} \times \text{Correction factor (from tables)} \times \text{Apparent specific gravity}$$

and

$$\text{Specific yield} = \text{Porosity} - \text{Specific retention}.$$

Specific yields of 76 samples from 7 test holes, thus calculated, have been shown in figure 17. [Table 25 has been interpreted from fig. 17 by A. I. Johnson.] From

TABLE 24.—*Specific yield values used in coastal plain of Los Angeles County, Calif.*

[After State Water Rights Board Revised Values of Specific Yield as used for San Fernando Valley Reference, 7–9–59, which is based on values used in Bulletin 45, Geology and Ground Water Storage Capacity of Valley Fill]

Note: Specific yield values above base of Bellflower aquiclude=00

00 Percent—Bellflower Aquiclude

03 percent—Clay and shale

Adobe	Granite clay	Shale
Boulders in clay	Hard clay	Shaley clay
Cemented clay	Hard pan	Shell rock
Clay	Hard sandy shale	Silty clay loam
Clayey loam	Hard shell	Soapstone
Decomposed shale	Muck	

05 percent—Clayey sand and silt

Chalk rock	Rotten conglomerate	Sediment
Clay and gravel	Rotten granite	Shaley gravel
Clayey sand	Sand and clay	Silt
Clayey silt	Sand and silt	Silty clay
Conglomerate	Sand rock	Silty loam
Decomposed granite	Sandstone	Silty sand
Gravelly clay	Sandy clay	Soil
Loam	Sandy silt	

10 percent—Cemented or tight sand or gravel

Caliche	Dead gravel	Heavy rocks
Cemented boulders	Dead sand	Soft sandstone
Cemented gravel	Dirty pack sand	Tight boulders
Cemented sand	Hard gravel	Tight coarse gravel
Cemented sand and gravel	Hard sand	

14 percent—Gravel and boulders

Cobbles and gravel	Heaving gravel	Silty sand
Coarse gravel	Heavy gravel	Tight fine gravel
Boulders	Large gravel	Tight medium gravel
Broken rocks	Rocks	Muddy sand
Gravel and boulders	Sand and gravel, silty	

16 percent—Fine sand

Fine sand	Quicksand	Sand, gravel and boulders
Heaving sand	Sand and boulders	Tight sand

21–23 percent—Sand and gravel

Dry gravel	Gravelly sand	Sand
Loose gravel	Medium gravel	Water gravel

26 percent—Coarse sand and fine gravel

Coarse sand	Fine gravel	Medium sand

Value of one added to given value where streaks of sand or gravel occur in clay or clayey material.

this data the average specific yields of various grades of sediments have been computed and have been used to calculate the mean specific yield for a thickness of 400 feet of sediments penetrated by each test hole. Based on this average specific yield, the subsurface sediments in the Rechna Doab have been zoned as shown in figure 18.

* * * * * * *

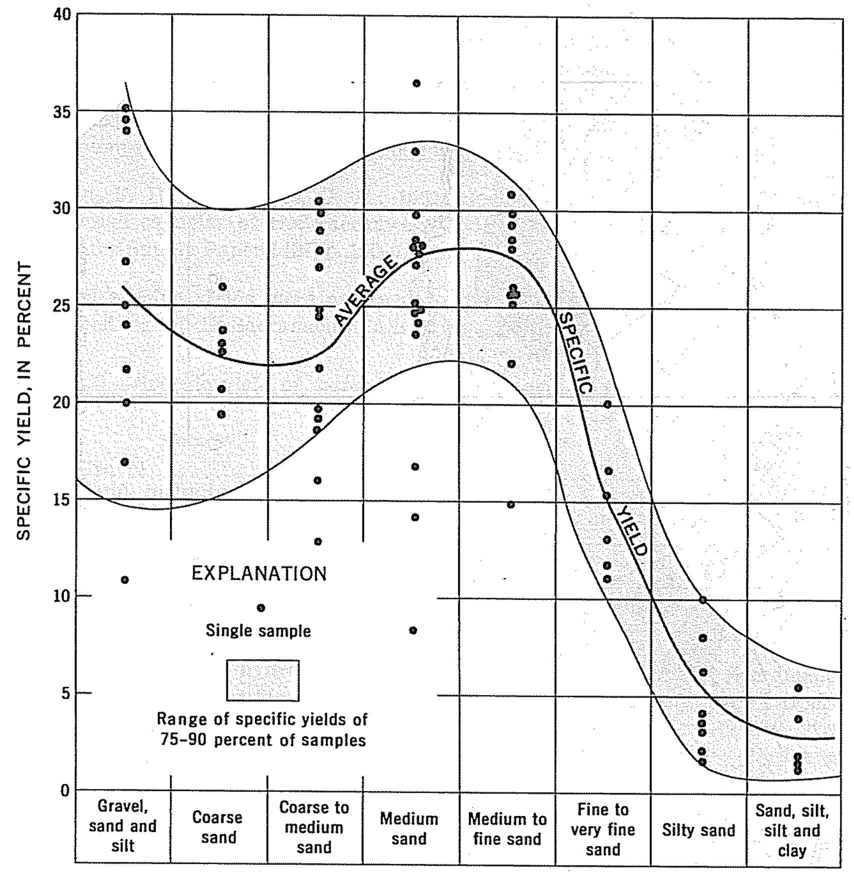


FIGURE 17.—Relation of specific yield to particle size for sediments sampled at Rechna Doab, West Pakistan. (After Kazmi, 1961.)

TABLE 25.—*Specific yield of alluvium from Rechna Doab, West Pakistan*

Material	*Specific yield (percent)*
Gravel, sand and silt	26
Coarse sand	23
Coarse to medium sand	23
Medium sand	28
Medium to fine sand	27
Fine to very fine sand	15
Silty sand	5
Sandy silt, silt and clay	3

Under the water table conditions the specific yield of an aquifer equals coefficient of storage. Thus the coefficient of storage as deduced from the behaviour of the rising water table * * *, in Rechna Doab varies from 0.2 to 0.3 * * *. As deduced from the laboratory studies, the average storage coefficient for the entire aquifer in the Rechna Doab, is 0.17; in the northeastern part of the doab the aquifer has an average specific yield of about 0.14; in the central zone

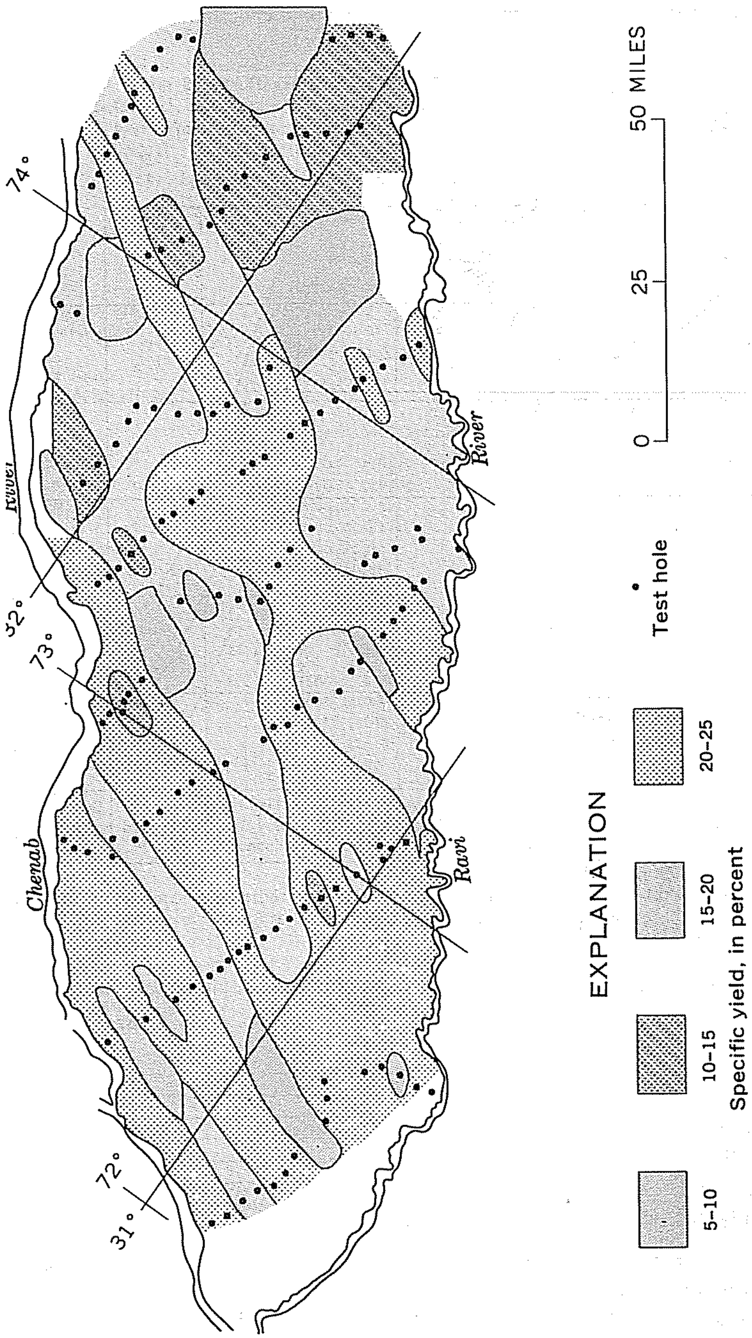


FIGURE 18.—Specific yield of sediments of Rechna Doab, West Pakistan. (After Kazmi, 1961.)

(largely waterlogged) the average is about 0.2 and in the southeastern portion of the doab the average is 0.19. However these figures are much higher than those obtained from aquifer tests according to which the storage coefficient ranges from 0.0016 to 0.073 at various locations * * *. This wide range of variation is readily explained by the fact that some of the sand zones between the clay layers, in the pumped wells, have probably been under artesian or semiartesian pressure.

Olmsted, F. H., and Davis, G. H., 1961, Geologic features and ground-water storage capacity of the Sacramento Valley, California: U.S. Geol. Survey Water-Supply Paper 1497, p. 150–152.

Modified specific yields were assigned to the five groups of material classified in the well logs of the Sacramento Valley [table 26].

* * * * * * *

TABLE 26.—*Specific yield of water-bearing sediments in the Sacramento Valley, Calif.*

Material	*Specific yield (percent)*
Gravel	25
Sand, including sand and gravel, and gravel and sand	20
Tight sand, hard sand, fine sand, sandstone, and related deposits	10
Clay and gravel, gravel and clay, cemented gravel, and related deposits	5
"Clay," silt, sandy clay, lava rock, and related fine-grained deposits	3

The lithologic and hydrologic character of the sediments of the Sacramento Valley necessitated certain modifications of the specific yields obtained by experiments in earlier investigations. The conditions under which alluvial deposition occurred in the Sacramento Valley were different from those in the other area and are the principal reason for the modifications.

In contrast to the south-coast basin where continental sediments, composed essentially of alluvial-fan deposits, were laid down by intermittent streams of steep gradient, the sediments of the Sacramento Valley are predominantly slack-water deposits laid down by the Sacramento River and its tributaries on broad, flat, alluvial plains and fans. In general, the alluvial deposits of the south-coastal basin are much coarser than those of the Sacramento Valley. Also, most of the clay in the pre-Recent deposits of the south-coast basin is the result of weathering rather than deposition from water; hence, a gravel deposit may contain considerable clay in the form of weathered pebbles that would not reduce the permeability of the deposit as much as would an equal amount of interstitial clay deposited from water.

The samples tested in the Mokelumne area are not considered representative of the sediments in the 20- to 200-foot depth range in the Sacramento Valley, because they were all taken at depths of less than 15 feet in unconsolidated deposits of late Pleistocene and Recent age. Most of the wells drilled to a depth of 200 feet penetrate sediments of early Pleistocene and Pliocene age throughout the eastern and northern parts of the valley. These older deposits are more indurated and presumably of lower specific yield than the younger alluvium.

Probably the most important departure from the experimental results was the specific yield of 20 percent assigned to the sand category. It is believed that material ordinarily logged as sand by well drillers in the Sacramento Valley is somewhat more consolidated and hence of lower specific yield than sand in the south-coastal basin and sand samples from the younger alluvial deposits of the Mokelumne area. Facts tending to support this idea are that drillers frequently distinguish the unconsolidated sand from the more or less consolidated sand by use of the terms "loose sand," "running sand," "quicksand," and "caving sand"; and that a considerable part of the water-bearing deposits of the eastern and northern parts of the Sacramento Valley are firm enough to stand without casing * * *.

Enough well logs mentioned tight sand, hard sand, sandstone, cemented sand, and other descriptive terms indicating restricted permeability that an intermediate category was set up with an assigned specific yield of 10 percent.

A specific yield of 5 percent was assigned deposits such as clay and gravel, "dry" gravel, cemented gravel, and gravelly clay, which although they are obviously of low permeability, supply small quantities of water to wells.

The fine-grained deposits, including clay, silt, sandy clay, hardpan, muck, shale, volcanic ash, and lava, were assigned a specific yield of 3 percent. In any one well log, deposits included in this category generally constitute more than half the sediments penetrated in the 20- to 200-foot depth range; only locally do the coarse-grained deposits occupy more than half this depth range. The specific yield of 3 percent is higher than that used for clay in the study of the south-coast basin, but it is midway between the values used for clay and sandy clay in the unweathered subsurface alluvial deposits in that area. Material logged by the drillers as "clay" is likely to include many beds that are silty, sandy, or even gravelly, if they contain much material so fine that it remains in suspension in the drilling fluid * * *.

The specific yield of 25 percent assigned to gravel agrees fairly closely with experimental results obtained by Eckis (Eckis and Gross, 1934) and by Piper (Piper and others, 1939).

Cohen, Philip, 1963, Specific-yield and particle-size relations of Quaternary alluvium, Humboldt River valley, Nevada: U.S. Geol. Survey Water-Supply Paper 1669–M, p. 20–23.

The data and graphs [table 27] * * * show the relations, or lack of relations, that seem to exist between specific-yield, porosity, specific-retention, sorting-coefficient, and median particle-size-diameter values of 323 samples from the Humboldt River valley. In summary, these apparent relations are:

TABLE 27.—*Specific yields for alluvial deposits in the Humboldt River valley, Humboldt County, Nev.*

Material	*Specific yield (percent)*
Fine gravel	19
Very-fine gravel	18
Very-coarse sand	21
Coarse sand	27
Medium sand	28
Fine sand	26
Very-fine sand	20
Silt	19
Clay	.5

1. For most samples, porosity values are virtually independent of sorting-coefficient values alone.
2. Porosity values tend to increase as median particle-size-diameter values decrease.
3. For most samples, specific-retention values do not correlate with sorting-coefficient values alone.
4. Specific-retention values tend to increase as median particle-size-diameter values decrease.
5. Specific-yield values do not correlate with sorting-coefficient values of samples whose median particle-size-diameter values fall within the silt- and gravel-size ranges but tend to increase as sorting coefficient values decrease in the intervening ranges.
6. There is a poor correlation between specific-yield values and median particle-size diameter values.

* * * * * * *

* * * the specific-yield values of the samples from the Humboldt River valley differ markedly from those shown by the other writers. The most striking difference is the tendency for samples from the Humboldt River valley to have considerably higher mean specific-yield values for samples whose median particle-size diameters fall within the silt-size range.

The relatively high specific-yield values of the samples whose median diameters are in the silt-size range probably partly is a result of the relatively high porosity of this material * * *.

Preuss, F. A., and Todd, D. K., 1963, Specific yield of unconsolidated alluvium: Berkeley, California Univ. Walter Resources Center Contr. 76, p. 2–4, 13, 16, 19.

Because of the amount of data available from previous investigations, this study was restricted to the analysis of published data. However, it was necessary to assume (a) that the data from each of the four sources * * * were comparable; and (b) that the data were representative of what would be expected from other alluvial sources.

Several studies have indicated that gravity drainage of fine-grained materials, such as clay or silt, is a very slow process. Therefore, specific yield, as a measure of the ultimate volume of water drained, is seldom attained under field or laboratory conditions. Water yield is not constant but increases with time at an ever diminishing rate. Because the four data sources did not make any particular distinction with regard to their values, it will be assumed here that the samples had undergone complete drainage.

* * * * * * *

As the result of a thorough literature survey, four independent investigations were found to contain data presented in an usable form. From these investigations a total of 311 separate soil samples were selected for analysis in this study. The majority, 230 samples, was obtained from an extensive field investigation of the South Coastal Basin in the Los Angeles area of California. Porosities and specfic retentions were determined in the laboratory, and specfic yields were obtained as the difference.

From an investigation of the ground water aquifer in South-Central Kansas, 28 samples were obtained, and 32 samples came from a study in South-Central Nebraska. In both of these studies, porosities and moisture equivalents were determined in the laboratory. * * *.

The remaining 21 samples were obtained from a ground water study of the Mokelumne area of California. The porosity and specific yield were determined in the laboratory for that study.

* * * * * * *

To determine which grain diameter was the most representative, the average deviation of specific yield values within plus or minus one standard error of estimate was plotted against the representative grain diameter. * * * It indicates that a representative grain diameter of about D_{50} has the least degree of specific yield deviation.

* * * * * * *

It appears that a maximum value of specific yield occurs with a D_{50} of between 0.4 and 0.5 of a millimeter. As the grain sizes become smaller beyond this point, the interstices also become smaller producing increased capillary forces. These increased forces result in greater retention of the water so that specific yield decreases. The large range in specfic yield for any particular grain size can be largely attributed to variations in porosity.

A relationship between uniformity coefficient and grain size resulted in no definite conclusions. However, it was noted generally that, for the samples used in this study, the uniformity coefficient decreases as the grain size decreases. * * *.

The results * * * indicate that porosity has perhaps the greatest single effect upon specific yield. It appears that a peak specfic yield of 32.5 percent occurs at a porosity of between 41 and 42 percent. After the peak the specfic yield seems to diminish quite rapidly.

* * * * * * *

[Table 28 was interpreted by A. I. Johnson from data in this report.] * * * The resulting colinear graph [fig. 19] shows the relation of D_{50} to specific yield for various porosities.

TABLE 28.—*Specific yields of unconsolidated alluvium*

Material	*Specific yield (percent)*
Coarse gravel	12
Medium gravel	13
Fine gravel	17
Gravelly sand	22
Coarse sand	28
Medium sand	28
Fine sand	23
Very fine sand	16
Silt	4

It is interesting to note that the family of lines has a characteristic shape. The range of specific yield is relatively broad for the same grain size. This broad range shows the importance of porosity. The flattening of the lines of porosity toward a constant specific yield value, always less than the porosity, indicates that specific retention approaches a finite value greater than zero.

SUMMARY

Table 29 summarizes the specific yields used in many of the previously listed investigations. A specific yield averaged from all values reported in the table also is reported for each texture of rock or soil material. The reported specific yields, in general, are representative of the ultimate amount of time for drainage. Corrections to lower values would have to be made for short drainage periods.

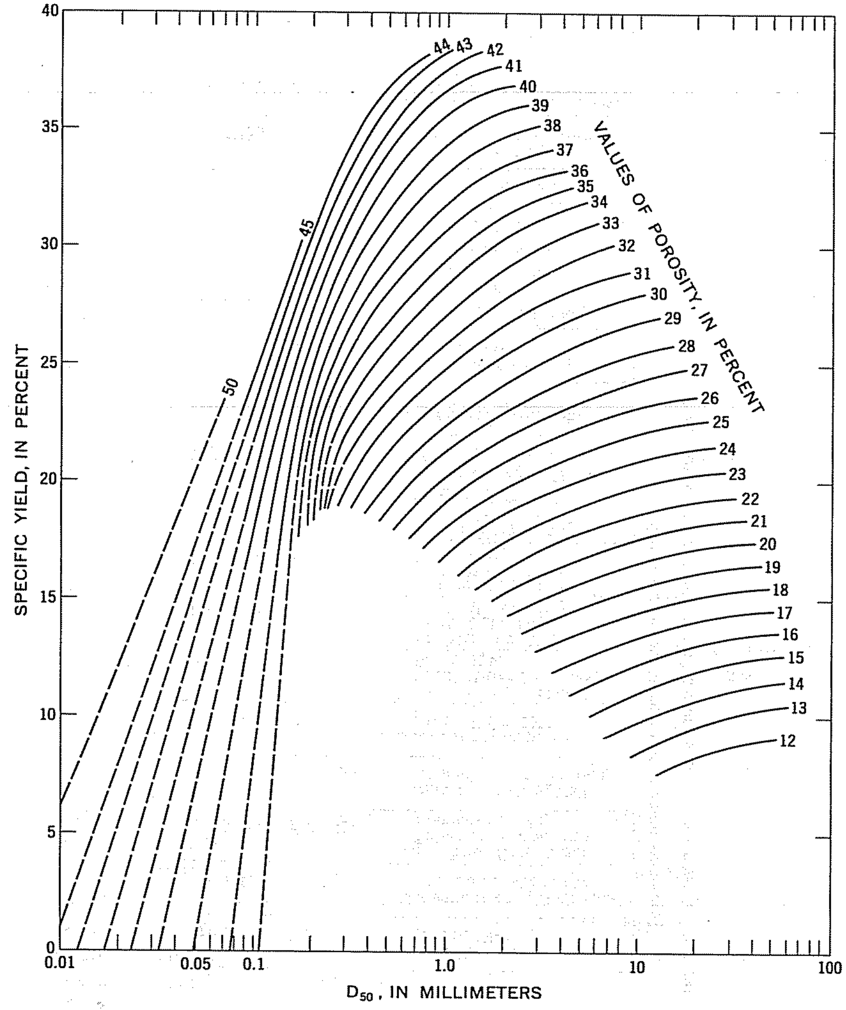


FIGURE 19.—Colinear plot of D_{50} to specific yield for various values of porosity. (After Preuss and Todd, 1963.)

It should be remembered that the textures listed are, in general, broad classifications based on the predominate particle size. One can observe that the highest specific yields tend to be around the medium and coarse sand texture—this is due to the fact that these sands normally have a more uniform size distribution than do the gravels or the finer sands, silts, and clays.

Research on specific yield completed by the Hydrologic Laboratory indicates that many of the specific yields used in the past—especially for fine-textured materials such as the silts, sandy clays, and fine sands—are too small. Johnson and Kunkel (1963) pointed out that this

TABLE 29.—*Compilation of specific yields for various materials*

[All values rounded off to nearest whole percentage]

Material	Valley fill, California (Eckis, 1934)	Mokelumne area, California (Piper and others, 1939)	Santa Ynez River basin, California (Upson and Thomasson, 1951)	Sacramento Valley, Calif. (Poland and others, 1949)	Smith River plain, California (Back, 1957)	Ventura County, Calif. (Calif. Water Resources Board, 1956)	Santa Margarita Valley, Calif. (Calif. Dept. Public Works, 1956)	Tia Juana Basin, Calif. (Calif. Water Rights Board, 1957)	San Luis Obispo County, Calif. (Calif. Water Resources Board, 1958)	San Joaquin Valley, Calif. (Davis and others, 1959)	Eureka area, California (Evenson, 1959)	Santa Ynez Basin, Calif. (Wilson, 1959)	Rechna Doab, Pakistan (Kazmi, 1961)	Napa-Sonoma Valleys, Calif. (Kunkel and Upson, 1960)	Humboldt River Valley, Nev. (Cohen, 1963)	Unconsolidated alluvium (Preuss and Todd, 1963)	Little Bighorn River valley, Montana (Moulder and Others, 1960)	Average specific yield
Clay	1	4	2	3	1	0	1	1	3	3	3	5	3	3	1			2
Silt	10	4	12	3		3	10	10	5	5	10	5	5	5	10	4	17	8
Sandy clay	10	4	12	3	5	5	5	5	5	5	10			10				7
Fine sand	21	26	12	10	10	25	28	25	25	10	20	20	27	20	26	23	32	21
Medium sand	31	26	30	20	15	25	28	30	25	25	20	30	28	20	28	28	32	26
Coarse sand	31	35	35	20	25	25	28	32	25	25	20	30	23	20	27	28	32	27
Gravelly sand	31	35	35	20	25	21	22	28	21	25	20		23	20		22	32	25
Fine gravel	27	35	35	25	25	21	22	26	21	25	25	25	26	25	19	17	25	25
Medium gravel	21			25	25	21	22	23	21	25	25	25	26	25		13	25	23
Coarse gravel	14			25	25	21	22	18	21	25	25	25	26	25		12		22

conclusion is indicated by specific yields obtained by various field tests as well as by the centrifuge, column-drainage, and moisture-tension tests in the laboratory. These authors also noted that the specific yield varies depending on the interrelation of textures; for example, a silt over a sand may not have as high a specific yield as would the same silt over a clay.

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