SPECIFIC YIELD BY GEOPHYSICAL LOGGING POTENTIAL FOR THE DENVER BASIN

by

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ABSTRACT

Management of the ground-water resource residing in the bedrock aquifers of the Denver Basin requires estimation of the volume of water ultimately recoverable from these formations. The aquifers now exist under confined conditions, except near the outcrops, and conventional field methods for estimation of specific yield are not applicable.

Management of the waters in the bedrock aquifers of the Basin would be greatly expedited by a method that would permit objective estimation of specific yield on a routine basis. This report reviews the concept of specific yield, usual methods for its estimation, and the potential for use of bore-hole geophysical measurements as an alternate method for estimating specific yield. The nuclear magnetic log emerged as the most promising bore-hole geophisical technique. This log measures the spin-lattice relaxation time of hydrogen nuclei after being subjected to a magnetic field. The response is believed to be proportional to the 'free' fluid per unit volume of porous medium, and is xpected to closely correspond to the drainable water. A program of combined coring, nuclear magnetic logging, and laboratory measurement will be required to evaluate the procedure.

TABLE OF CONTENTS

INTRODUCTION

The Denver Basin is a north-south trending synclinal structure bounded on the west by the Front Range and on the east by the High Plains. The portion of the basin of interest in this report extends northward to Greeley, Colorado and southward to somewhat beyond Colorado Springs and underlies approximately 6000 square miles of land surface. The basin consists of a number of sedimentary geologic units overlying Precambrian crystalline rocks that form the basement. Several sedimentary formations within this sequence constitute aquifers and are commonly referred to as the bedrock aquifers of the Denver Basin.

Large quantities of water, suitable in quality for almost any purpose, are stored in these aquifers. Increasingly, the ground waters in the bedrock aquifers are being used to meet the increasing demands for water associated with the population growth in the Front Range urban corridor. Some areas (e.g. the South Platte River corridor and the Strasburg-Byers-Deer Trail area) have experienced precipitous declines in water levels over the last decade.

Central to the prudent management of these ground waters is the relation between the drawdown of water levels and the volume of water recovered. Except near the outcrop areas along the edges of the basin, the bedrock aquifers are artesian (confined). Under artesian conditions, the relationship between drawdown of water levels and the volume of water recovered is governed by the slight expansion of water and the compression of the aquifer that results from a reduction of pore-water pressure. Because both water and rocks are only slightly compressible, large and extensive drawdowns are associated with water removal from artesian aquifers.

Continued removal of water from an artesian aquifer eventually causes the water levels to fall to the elevation of the top of the aquifer and the aquifer becomes unconfined. At this point, the relationship between the volume removed and the change in water level is modified dramatically. Typically, the total volume of water recoverable under artesian conditions is less than 0.1 percent of the volume of water stored in the aquifer. In contrast, the volume recoverable once the aquifer becomes unconfined typically ranges from 10 to perhaps 60 percent of stored volume. The salient difference between the artesian and unconfined condition is the physical drainage of pores and consequent replacement of air that occurs once the aquifer becomes unconfined.

Traditionally, the relation between the volume of water removed and the associated drawdown is quantified by the storage coefficient in the case of artesian conditions and by the specific yield in the case of unconfined conditions. Field aquifer tests, performed by pumping and observing the corresponding drawdown, are the most reliable methods for estimation of these two important hydrologic parameters. However, field aquifer tests for the estimation of specific yield are applicable only if the aquifer is unconfined. Thus, if one seeks to estimate the quantity of water ultimately recoverable from an artesian aquifer, methods other than the traditional aquifer test must be utilized to estimate the specific yield. Because the volume of recoverable water is comprised almost entirely of water recovered under unconfined conditions, any uncertainty in the estimate of specific yield is directly reflected as a corresponding uncertainty in the estimated recoverable volume. Even small differences between independent estimates of specific yield can represent large differences in estimated recoverable volumes with attendant important economic ramifications.

The objective of this study was to survey and review the various indirect methods by which the specific yield of the artesian aquifers of the Denver Basin might be estimated. Well bore geophysical methods emerged as deserving special consideration and are emphasized in this report. The concept of specific yield is discussed in some detail as a means of providing background and perspective for subsequent discussions of the principles on which the geophysical techniques are based.

GEOHYDROLOGY OF THE DENVER BASIN

The Denver Basin comprises a portion of the Colorado Piedmont Section of the Great Plains physiographic province. The climate is semi-arid with mean annual precipitation ranging from 11 to 17 inches, a large fraction of which occurs as thunder storms in the summer months. Surface drainage in the basin is divided into a portion that flows to the South Platte River and a portion that forms part of the Arkansas River watershed. The major streams in the portion within the South Platte catchment include Plum Creek, Bear Creek, Cherry Creek, Clear Creek, Box Elder Creek and Bijou Creek. The South Platte River enters the basin a few miles southwest of Denver and flows in a general northerly direction to Greeley where it turns eastward toward the High Plains region. Streams flowing to the Arkansas River include Monument Creek, Jimmy Camp Creek, Black Squirrel Creek, Horse Creek and Big Sandy Creek. Streams whose head waters are located within the basin (most in the Black Forest area) are ephemeral (Colorado Division of Water Resources, 1976).

Description of Bedrock Aquifers

The important bedrock aquifers of the Denver Basin are, in descending order; the Dawson, Denver, and Arapahoe formations of the Dawson Group; the Laramie-Fox Hills formations; and the Dakota, Lyons, and Fountain formations.

The Dawson Arkose is the uppermost of the aquifers in the Upper Cretaceous Dawson Group. It consists of interbedded sandstone, conglomerate, shale, and clay comprising a total thickness of as much as 1100 ft. According to the Colorado Division of Water Resources (1976), the lower 400-500 ft consists mainly of coarse, arkosic and micaceous sandstone and is the principal water bearing zone within the Dawson aquifer. Immediately below the Dawson Arkose, the Denver formation consists of a series of sandstones that thin toward the east and become interbedded with clays and shales. The sandstones are poorly developed in the southern portion of the basin and, locally, grade to shale.

The lowest member of the Dawson Group is the Arapahoe formation which ranges in thickness from 500 to 600 ft. The lithology is dominated by sandstone and conglomerate. Some 300 ft or more of sandstone is locally present and provides a reliable source of water of good quality.

The Laramie-Fox Hills aquifer is the next significant aquifer below the Arapahoe. This aquifer includes the Milliken sandstone of the Fox-Hills formation and the A and B sandstones of the overlying Laramie. The portion of the Laramie formation extending between the top of the B sandstone and the base of the Arapahoe is thought to be the confining stratum for the Laramie-Fox Hills aquifer. The average thickness of the Laramie-Fox Hills aquifer is 200 ft but ranges upward to about 400 ft. Individual sandstone strata form the water bearing intervals and are often separated by 5-20 ft of shale. Locally, 100-250 ft of net sandstone thickness is available for water production.

The Dakota aquifer consists of the upper 100 ft of the South Platte and Lytle formations of the Dakota Group. Ground waters of usable quality are found in the Dakota only near the west boundary of the basin where the Dakota outcrops.

Like the Dakota aquifer, the Fountain formation and the Lyons sandstone are useful aquifers only near the outcrop on the western side of the basin. These aquifers are Permian in age and are separated from the Dakota by Lykins, Ralston Creek, and Morrison formations.

Except near the outcrop areas, all of the above aquifers are artesian. Confining beds are clay and shale strata, but are not believed to preclude vertical communication between the Dawson Arkose, the Denver, the Arapahoe, and the Laramie-Fox Hills. The piezometric head is generally greatest in the uppermost aquifer (i.e. the Dawson Arkose) and decreases with depth to the Laramie-Fox Hills, at least in the undisturbed, pre-development state. This downward gradient is thought to result in some small downward movement of water from aquifer to aquifer.

The hydraulic properties of the aquifers vary substantially, both within individual aquifers and from aquifer-to-aquifer. Table 1 contains hydraulic properties believed to be typical of the water bearing strata. Wells completed in these bedrock aquifers exhibit specific capacities ranging from 0.1 to 3.0 gpm/ft.

TABLE 1

TYPICAL HYDRAULIC PROPERTIES OF THE BEDROCK AQUIFERS IN THE DENVER BASIN
(Adapted from Division of Water Resources, 1976)

Aquifer	K ft/d	T ft^2/d	S	Sy
Dawson Arkose	2.7-6.9	70-700	0.002-0.09	0.15-0.25
Denver	1.3-2.7	30-270	0.002	0.10-0.15
Arapaho	2.7-6.9	70-700	0.002-0.09	0.20-0.25
Laramie-Fox Hills	1.3-4.7	130-940	0.0004	0.15-0.20
Dakota	0.4	13- 30	0.001	0.10
Lyons-Fountain	0.7-1.3	70-130	0.0001	0.02-0.05

K = hydraulic conductivity
T = transmissivity
S = storage coefficient
Sy = specific yield

TABLE 2

WATER SUPPLY CHARACTERISTICS OF MAJOR AQUIFERS
(Adapted from Division of Water Resources, 1976)

Aquifer	Stored Vol ac-ft	Recoverable Vol ac-ft	Pumped Vol ac-ft/yr	Total Recharge ac-ft/yr	Natural Discharge ac-ft/yr
Dawson Group	$236x10^6$	$117x10^6$	124000	110000	5200
Dawson	$35x10^6$	$17x10^6$			
Denver	$31x10^6$	$15x10^6$			
Arapahoe	$170x10^6$	$85x10^6$			
Laramie-Fox Hills	$66x10^6$	$34x10^6$	16500	10000	?

Recharge, Discharge, and Storage

Table 2 contains a summary of the water supply estimates for the major aquifers in the basin. The data are a summary of estimates made by the Colorado Division of Water Resources (1967), and are intended only as rough indices. In particular, the volumes of recoverable water are rough estimates based on generalized values of specific yield that remain a source of controversy.

As indicated in Table 2, the three aquifers of the Dawson Group are the most significant from a regional perspective. It is believed that these aquifers receive recharge from precipitation on outcrop and subcrop areas, along fault zones near the Front Range, and from stream seepage in the Black Forest area. Total recharge to the Dawson Group aquifers is indicated at about 110,000 ac-ft/yr in Table 2. A recent study by the USGS suggests that natural recharge to the Dawson Group aquifer may total only about 35,000 ac-ft/yr (Robson, 1984). Most of this recharge occurs in the uppermost aquifer, the Dawson Arkose, and the lower two aquifers are supplied mainly through vertical leakance. This study also suggests that the Dawson Group aquifers have the potential for discharging to streams within the basin. Under conditions prevailing prior to development, Robson (1984) suggests that all of the 35,000 ac-ft/yr were eventually discharged to streams. From the Dawson Arkose, the major recipient streams are the Plum, Cherry, Box Elder, Kiowa, and Monument-Fountain. Robson indicates that the Denver and Arapahoe formations discharged, under pre-development conditions, a total of about 11,000 ac-ft/yr. Most of the discharge from these two lower aquifers in the Dawson Group was received by the Plum and Bijou Creeks and by the South Platte River.

Robson (1984) indicates recharge to the Laramie-Fox Hills aquifer at about 4,000 ac-ft/yr. Again, under pre-development conditions, it is suggested that this quantity of water is discharged to surface streams, the major recipients being the Bijou, San Arroya, and Badger Creeks. A small discharge (less than 400 ac-ft/yr) to the South Platte from the Laramie-Fox Hills is indicated.

Summary

The most significant bedrock aquifers of the Denver Basin are the Dawson Arkose, the Denver, the Arapahoe, and the Laramie-Fox Hills. Locally important, but less important regionally, are the Dakota, Fountain, and Lyons aquifers. Total volume in storage in the Dawson Group and Laramie Fox Hills aquifers is 250-300 million ac-ft. Total recharge to these units is on the order of 40,000-100,000 ac-ft/yr. All of the Dawson Group aquifers and the Laramie-Fox Hills aquifer have potential for discharging to surface streams within the basin.

THE CONCEPT OF SPECIFIC YIELD

The concept of specific yield arose and endures because it provides a simple and convenient means for relating the volume of water withdrawn from an unconfined aquifer to the consequent lowering of the water table. Nevertheless, a precise, unambiguous definition of specific yield remains elusive, largely because the concept is an attempt to incorporate several physical processes into a single, bulk parameter. Freeze and Cherry (1979) define specific yield as 'the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table'. This definition is reflective of the manner in which the concept is most often used and measured in the field. McWhorter (1977) used the words 'apparent specific yield' to refer to this bulk, field-measured parameter which includes such site specific influences as entrapped air, stratification of materials above the water table, water-table position, and rate of change of water-table elevation. Other definitions refer to the difference between the porosity and the volumetric water content below which moisture cannot be drained by gravity (Smith, 1961; DeWiest, 1965). The following brief discussion of the physics of pore-water drainage is intended to provide a basis for understanding the concept of specific yield in the context of the physical processes that influence the yield derived from unconfined aquifers.

Physics of Pore-Water Drainage

We focus attention on a unit area, vertical column of geologic materials extending upward from an impervious, aquifer base. Initiation of pumping from a nearby well causes a zone of reduced pressure to expand outward, lowering the water table. The water above the water table in the column of interest experiences a reduced pressure (an increase in suction) as the result of the decline in water table level. Air-water interfaces within the pores of the unsaturated zone tend to recede as a result of the increased suction so that the radii of curvature of the interfaces are such that the tangentially acting forces of surface tension remain in balance with the forces resulting from suction. It is necessary that water be expelled from the pores and replaced by air in order to accommodate the recession of the interfaces. Thus, the increase in suction associated with a reduced water-table elevation results in drainage of the pores.

The functional relation between the volume of water retained per unit volume of porous solid and the suction is fundamental in the drainage phenomenon, both with respect to the rate at which drainage occurs and to the volume drained between any two equilibrium states. This relation is variously referred to as a capillary-pressure desaturation curve, a moisture-retention curve, or the moisture characteristic curve. Example moisture retention curves are shown in Figure 1.

The moisture retention curve is usually regarded as being a characteristic of the material on which it is measured. As such it is applied to unsteady and steady flows and to equilibrium conditions. However, it differs greatly from material-to-material. Many different moisture retention curves may be required to characterize the retention of water in a column of nonhomogeneous material.

Drainage from the column of unsaturated materials extending above the water tables does not occur instantaneously in response to a reduced water table level. Rather, it is a time-dependent process and the volume drained approaches its ultimate, maximum value asymptotically in time. It is common practice to handle the 'delayed yield from storage' in an

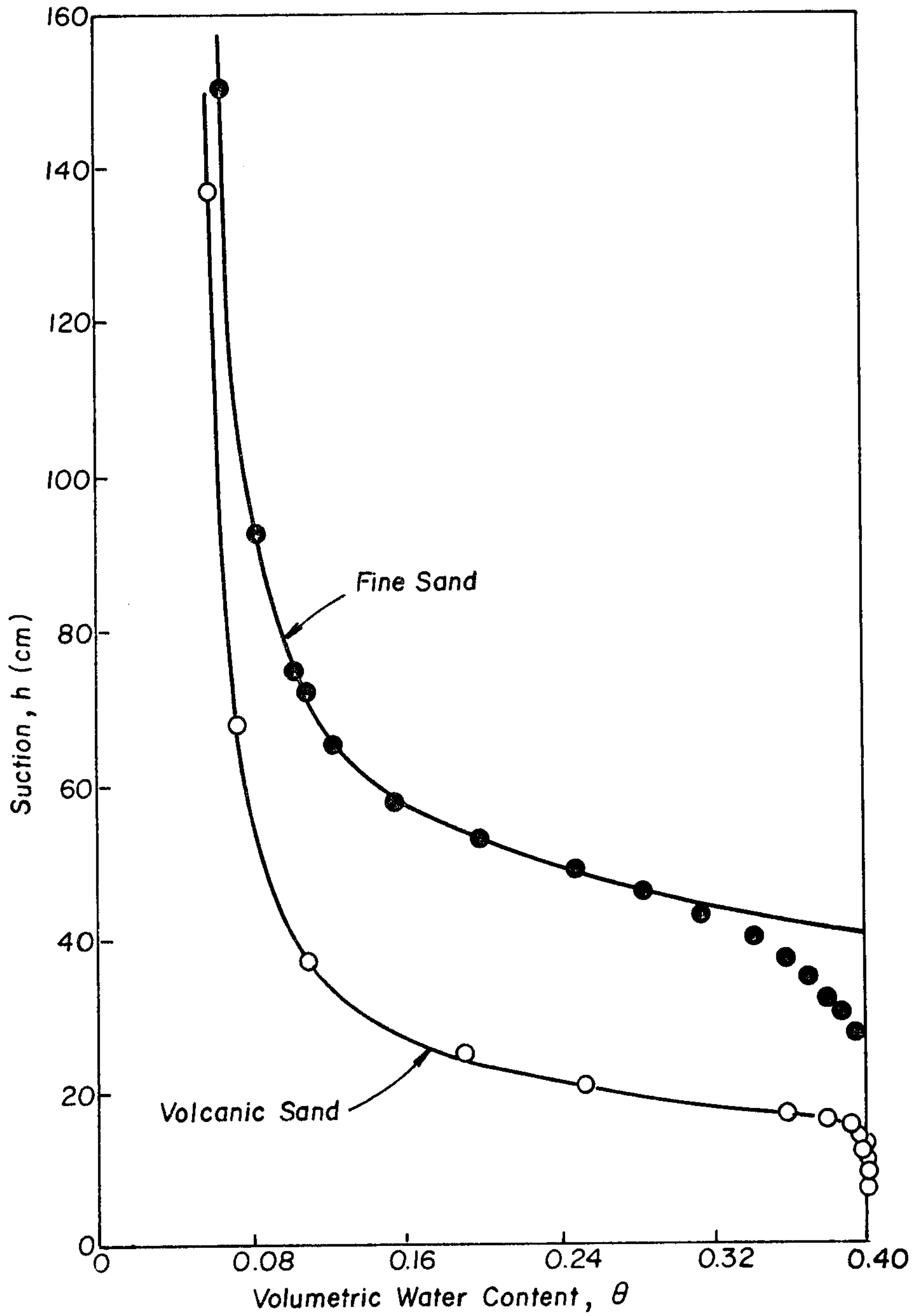

Figure 1. Typical Moisture Retention Curves

approximate way that does not require explicit knowledge of either the moisture retention curve or the hydraulic conductivity - suction relation. Often, field tests are conducted for long time periods in an effort to assure that drainage to near equilibrium conditions has occurred in the unsaturated zone. In either case, these procedures are in recognition of the fact that the specific yield is most useful when it refers to the volume drained between two equilibrium states.

We return now to a discussion of the moisture retention curve and its relation to specific yield as referred to the volume drained between two equilibrium states. It is observed from Figure 1 that the volumetric water content tends toward a constant value as the suction becomes increasingly large. This asymptotic value of water content is called specific retention and is often described as the 'water which cannot be drained by gravity'. Specific retention cannot be measured with complete objectivity and is associated with different suctions in different materials. Furthermore, specific retention has nothing whatsoever to do with gravity. It is, nevertheless, a more-or-less identifiable water content on the moisture retention curve, and in most aquifer-type materials represents a value at which further reduction requires large increases in suction.

The specific yield, defined as the volume of water released per unit area per unit decline in water table level, can be calculated from moisture retention data. This is conveniently accomplished by calculating the change in the unit area volume of air associated with a decline of the water table. The volume of air in the unsaturated zone per unit area is

$$V_a = \int_o^{z_1} (\phi - \theta)\,dh \tag{1}$$

V_a = volume of air per unit area

ϕ = porosity

θ = volumetric water content

h = height above the water table = suction

z_1 = distance from water table to top of aquifer.

In writing Eqn. 1, it was assumed that equilibrium conditions prevail so that the capillary suction at a point above the water table is numerically equal to the height of the point above the water table.

Equation 1, with z_1 replaced by z_2, applies for the calculation of air volume at a new water table level z_2. The difference between the two air volumes is equal to the volume drained or released per unit area. Thus, the specific yield, Sy, is expressible as

$$Sy = \frac{\int_o^{z_2} (\phi - \theta)\,dh - \int_o^{z_1} (\phi - \theta)\,dh}{z_2 - z_1} \tag{2}$$

Equation 2 provides a means of calculating the specific yield from moisture retention data. In a nonhomogeneous aquifer, say as the result of stratification, the retention function $\theta(h)$ will be different for each layer. This must be accounted for in the evaluation of the integrals.

In the ideal case of a homogeneous aquifer in which the distances z_1 and z_2 are equal to/or greater than the suction associated with the specific retention, Eqn. 2 becomes

$$Sy = \phi - \theta_r \tag{3}$$

in which θ_r is the specific retention. This is a commonly used defining relation for specific yield. Note, however, that it is equal to the volume of water released per unit area per unit decline in water table level only under special conditions.

It is important to recall that the above discussion of the relation of the moisture retention curve to the specific yield is based upon the assumption of equilibrium. It is not possible to calculate specific yield from moisture retention data alone for cases in which flow in the unsaturated zone is occurring. The reader is referred to discussions by Youngs (1969) and Raats (1974) that deal with the concept of specific yield under dynamic conditions.

Measurements of Specific Yield

The specific yield, defined as the volume of water released per unit area per unit decline in water table elevation, is the storage parameter in the Boussinesq formulation for unsteady flow in unconfined aquifers. The most widely used procedure for determining specific yield involves the selection of a value that causes a mathematical solution of the Boussinesq equation to most nearly agree with a corresponding set of data. The familiar constant-rate pumping test is the most common, although other flow situations have been used, particularly in agricultural drainage applications (van Schilfgaarde, 1974).

Laboratory determinations of specific yield are usually based on Eqn. 3. The difficulty in use of Eqn. 3 is in the measurement of θ_r, the specific retention. Because θ_r is associated with different suctions in different materials, it is not possible to establish a single suction as a standard at which θ_r is to be measured. In agriculture, θ_r is often taken as the moisture content at 1/3 bar suction. Other workers take θ_r

as the water content corresponding to 1,5, or 15 atmospheres. Probably the most reliable method for determining θ_r involves measurement of the entire water retention curve. Various methods for measuring the retention curve have been described (e.g. Corey, 1977; ASTM D 2325 and ASTM D 3152). These methods require the establishment of equilibrium conditions at a series of different suction values, and several days are often required to complete the measurements.

Under shallow water table conditions, the specific yield is often determined from Eqn. 2 with water content data measured in the field with moisture probes. Commonly, the neutron moisture meter is used to determine the integrated change in water volume in the unsaturated zone corresponsing to an observed and measured change in water table level. Bardhan (1975) provides an example of this method.

Because the specific yield is strongly dependent upon the porous material, there exists at least a rough correlation between specific yield and qualitative descriptions of the type of material. Table 3 contains a summary of specific yields based on Eqn. 3. Such generalized data are useful for estimating the range of values expected for a given site. This type of approach was used by Nordstrom (1984) to map the specific yield of the Ogallala aquifer in the Texas High Plains. Table 4 contains the correlation between specific yield and lithologic description used by Nordstrom.

TABLE 3

SPECIFIC YIELD OF AQUIFER MATERIALS
(Adapted from Morris Johnson, 1976)

Aquifer Material	No. of Analyses	Range	Arithmetic Range
Sedimentary Materials			
Sandstone (fine)	47	0.02-0.40	0.21
Sandstone (medium)	10	0.12-0.41	0.27
Siltstone	13	0.01-0.33	0.12
Sand (fine)	287	0.01-0.46	0.33
Sand (medium)	297	0.16-0.46	0.32
Sand (coarse)	143	0.18-0.43	0.30
Gravel (fine)	33	0.13-0.40	0.28
Gravel (medium)	13	0.17-0.44	0.24
Gravel (coarse)	9	0.13-0.25	0.21
Silt	299	0.01-0.39	0.20
Clay	27	0.01-0.18	0.06
Limestone	32	~ 0-0.36	0.14
Wind-Laid Materials			
Loess	5	0.14-0.22	0.18
Eolian Sand	14	0.32-0.47	0.38
Tuff	90	0.02-0.47	0.21
Metamorphic Rock			
Schist	11	0.22-0.33	0.26

TABLE 4

SPECIFIC YIELD ESTIMATED FROM LITHOLOGIC DESCRIPTIONS
OGALLALA AQUIFER - TEXAS HIGH PLAINS

Drillers' Lithologic Description	Specific Yield Percent
Rock or caliche	1
Rock, broken	14
Rock, honey-combed	27
Clay	2
Clay and fine sand stringers	8
Clay and medium sand stringers	9
Clay and coarse sand stringers	10
Clay, sandy	10
Silt	8
Pack sand	12
Sand, fine	21
Sand, medium	25
Sand, coarse	27
Sandstone, friable	14
Sandstone, cemented	5
Sand, medium and sandstone	20
Sand, fine and sandstone	17
Sand, fine and clay	11
Sand, medium and clay	14
Sand, coarse and clay	15

TABLE 4 (Continued)

SPECIFIC YIELD ESTIMATED FROM LITHOLOGIC DESCRIPTIONS
OGALLALA AQUIFER - TEXAS HIGH PLAINS

Drillers' Lithologic Description	Specific Yield Percent
Sand, fine and clay stringers	15
Sand, medium and clay stringers	18
Sand, coarse and clay stringers	19
Sand, fine and gravel	22
Sand, medium and gravel	24
Sand, coarse and gravel	25
Gravel, fine (pea)	25
Gravel, medium	23
Gravel, coarse	22
Gravel and clay	8
Gravel, sand, and clay stringers	18
Gravel, clay, and medium sand	17
Gravel, clay, and coarse sand	17

SPECIFIC YIELD AND BORE-HOLE GEOPHYSICAL MEASUREMENTS

As pointed out previously, the usual methods for determining the specific yield are, in general, not applicable to the bedrock aquifers of the Denver Basin in their present confined state. The exception is the procedure in which the moisture retention data $\theta(h)$ are measured for materials selected from cores. Such data, together with knowledge of the thicknesses of strata and expected ultimate water table levels, would permit evaluation of specific yield from Eqn. 2. Colorado State University, in cooperation with the Colorado Division of Water Resources and a private consultant, is currently in the process of carrying out such a program. Materials being used are from cores provided by the private consultant.

Evaluation of specific yield from Eqn. 2 with $\theta(h)$ data from cores has two major disadvantages from the perspective of routine operations. First, the coring operations and the time required to measure $\theta(h)$ at perhaps 25 or 30 points on the core causes the procedure to be expensive and untimely. Second, core recovery in many of the most important water bearing strata within the aquifer is often very poor. Even when samples of unconsolidated aquifer materials are successively obtained, it is very difficult to make the required measurements without undesirable disturbances.

The foregoing comments point to the need for a method of determining specific yield that is cost effective, timely, and capable of objective interpretation. The remainder of this report is devoted to a discussion of the potential for bore-hole geophysical techniques to contribute to such a procedure.

Scope and Perspective

Bore-hole geophysical measurements (well logging) are widely used to estimate the physical and chemical properties of geologic strata. Such measurements are often the most economical, and sometimes the only way, by which data on subsurface materials can be obtained. Rarely do geophysical methods measure directly the desired properties. Rather they usually measure a response to some induced phenomenon, and theoretical and empirical relations between the response and the physical/chemical properties are used to deduce the properties of interest. Progress in the technology and the quantitative interpretation of geophysical well logs has largely occurred in the petroleum industry where the economic incentive for knowledge of porosity, permeability, fluid distributions and etc. is high. Routine use of geophysical logs for quantitative determinations of aquifer properties in the ground-water industry has not kept pace, mainly because of the absence of sufficient economic motivation.

There are a great many different geophysical logs available for a variety of purposes. In the course of this study, essentially all modern geophysical logging methods were reviewed. Those selected for discussion in the following paragraphs are believed to have some potential for use in the determination of specific yield. It is emphasized that the large backlog of experience with these methods resides in the petroleum industry, where the hydrogeochemical conditions and physical parameters of interest are often greatly different from those in the ground water industry. While it was possible to assess the potential for application to the specific-yield determination based on the principles of the methods, the practical, scientific, and economic value of such applications must be assessed following the accumulation of direct experience in the Denver Basin.

Resistivity Logs

In the petroleum industry, resistivity logs have been used primarily for the detection of hydrocarbons and the estimation of hydrocarbon saturations. The method exploits the usual disparity that exists among the electrical conductivities of rock matrix, formation water, and hydrocarbons. In the absence of hydrocarbons, the interpretation of measured formation resistivities is greatly simplified. When hydrocarbons are not pesent, the principles of the method are conveniently summarized by the following two expressions:

$$R_o = FR_w \tag{4}$$

$$F = f(\phi) \tag{5}$$

where

R_o = resistivity of the water saturated porous medium

R_w = resistivity of the water

F = formation factor

ϕ = porosity.

The formation factor, F, accounts for the presence of the nonconductive solid matrix in the path of the electrical current and, therefore, is expected to be a function of porosity as indicated in Eqn. 5. Archie's (1942) empirical formula for the formation factor is

$$F = \phi^{-m} \tag{6}$$

where m is a dimensionless exponent called the cementation factor and takes values ranging from about 1.3 to 2.2.

The above equations permit, in principle, the determination of porosity from resistivity data. The formation resistivity, R_o, is measured and F is calculated from that value and knowledge of the resistivity of the formation water. The final step is to compute the porosity, ϕ , from Eqn. 6. Several practical difficulties exist, most of which are related to the measurement of true formation resistivity. In practice, the measured resistivity is affected by bore-hole geometry, chemical properties of the bore-hole fluid, mud-cake buildup, and invasion of the formation by the bore-hole fluid.

There are complicating factors in addition to those mentioned above. A somewhat minor one is related to the fact that not all of the water filled cross-section of the porous medium contributes equally to the transmission of electrical current. Perez-Rosales (1982, 1976) presents a semi-theoretical equation as a substitute for Eqn. 6 that accounts for 'stagnant' zones within the pore water. Equation 6 is a special case of the more general result. However, it is not clear that the fraction of pore water that is 'stagnant' in the context of electrical current transmission is related in any simple manner to the specific retention or irreducible water content that is important in the context of the specific yield problem.

A second factor that complicates the relation between measured formation resistivity and pore-water resistivity is the presence of clays in the porous medium. Insofar as clays effect the specific retention rather dramatically, the relationship between clay content and formation factor is of considerable interest to the problem at hand. At the present time, there are two models that have been advanced to account for observed relations between formation resistivity and pore-water resistivity in shaly sands: the Waxman-Smits (1968) cation exchange model and the dual-water model derived by Clavier, et al., (1977).

The Waxman-Smits model replaces Eqn. 4 with

$$C_o = \frac{1}{F^*} (BQ_v + C_w) \tag{7}$$

in which

C_o = conductivity of water saturated porous medium

C_w = conductivity of formation fluid

Q_v = concentration of sodium exchanges ions associated with the clay

B = counter ion equivalent conductance

Note that the conductivities in Eqn. 7 are the reciprocals of the corresponding resistivities and that Eqn. 7 reduces to Eqn. 4 when $Q_v = 0$ (i.e. when no clay is present). The coefficient B can be calculated from theoretical considerations.

Waxman and Smits (1968) further conclude that their F* is related to porosity by the Archie equation (i.e. Eqn. 6). Therefore, in principle one can determine the porosity, say from density and/or neutron logs, use the Archie equation to compute F*, and use measured C_o (from resistivity logs) and C_w data in Eqn. 7 to arrive at an estimate for Q_v. The quantity Q_v is the cation-exchange capacity per unit pore volume. As such, it might be expected to be strongly correlated with specific retention.

A first step in the evaluation of the feasibility of the above procedure would be to investigate whether a correlation between CEC and specific retention exists. A great deal of existing data on soils and other geologic materials could be used for such a purpose.

Thomas (1976) describes an apparatus that permits measurement of Q_v directly from drill cutting or side-wall cores. It is claimed that this apparatus is portable and could be used to construct a Q_v vs. depth log as the well is drilled and the cuttings sampled. If such a device performs as claimed and a good correlation between Q_v and specific retention could be demonstrated, then specific yield, as defined by Eqn. 3, could be estimated as a function of depth in the aquifer.

The dual-water model (Clavier, et al., 1977) also predicts a dependence of formation conductivity, C_o, on the CEC per unit of pore volume. The theoretical basis is different from the Waxman-Smit model, however. While the Waxman-Smits model has been used mainly as an aid to the interpretation of resistivity measurements in shaly sands, the dual-water model has found application in the interpretation of neutron life-time data. Thus, the discussion of the dual-water model is presented together with a review of the neutron life time logs in the next subsection.

<u>Neutron Life-Time Logs</u>

Various trade names exist for the geophysical instruments that use a cyclic source of high energy neutrons and measure the response as high energy capture gamma rays. In these devices, a pulse of high energy neutrons is electronically generated. Energy is lost as the neutrons invade the porous medium and after a time period on the order of 10 to 50 microseconds, they become low energy, thermal neutrons. They are then capable of being captured by the nucleus of atoms, in which case a high energy gamma-ray is emitted. The rate of decay of the flux of gamma rays from that source is a measure of the neutron capture cross-section of the formation.

The capture cross-section recorded on the log is comprised of the additive contributions of the solid matrix, the free water, the bound water, and the hydrocarbons, if present (Wiese, 1983). In the absence of hydrocarbons, the log-recorded capture cross-section can be expressed as:

$$\Sigma_L = v_m \Sigma_m + v_{wf} \Sigma_{wf} + v_{wb} \Sigma_{wb} \tag{8}$$

wherein

Σ = capture cross-section

v = volume per unit volume of porous medium

and subscript L refers to the measured (log) value, m to rock matrix, wf to free water, and wb to bound water. Clearly, the volume fractions in Eqn. 8 can be related to the total porosity (e.g. $v_m = 1 - \phi$). Manipulation of this equation, together with measurements of Σ_L in clean sands where no bound water is expected, eventually permits the calculation of the volume of bound water per unit volume of porous medium. The bound water is that which is associated with the clay minerals in the porous medium. Therefore, it does not include any capillary waters that might comprise a portion of the specific retention. In other words, the bound water in the dual water model is expected to be less than the specific retention. Coates, et al., (1983) provide a great deal of data in support of the dual-water model.

The rate of decay of the capture induced gamma rays is affected strongly by dissolved elements with high neutron capture cross-sections. Among these are chloride, lithium, and boron. Most applications of this method have been in high salinity waters containing chlorine. Apparently, successful use of the method in low salinity waters depends upon the presence of trace elements with very high capture cross-sections.

The direct way by which one can estimate the volume of bound water in shaly sands from neutron life-time measurements makes the method worthy of consideration. However, the fact that the derived volume of bound water does not directly correspond to specific retention and its problematic interpretation in low salinity waters does not make this method a likely candidate for application in the Denver Basin. One advantage of this log is that it can be run in cased holes. Examples of the use of the method are several and include Jameson, et al., (1977); Youngblood, (1980); Pennebaker III, (1980); Randall, et al., (1978).

Nuclear Magnetic Resonance

The nuclear magnetic log makes use of the theory of nuclear magnetic resonance applied to fluids confined in porous media. The nuclear magnetic log responds to hydrogen nuclei (protons). Protons spin on their own axes and, since they also carry an electric charge, generate small magnetic fields which cause the protons to act like tiny magnets. These dipoles precess because of the existence of the earth's magnetic field.

Creation of a magnetic field normal to the earth's field can cause the polarity of the dipoles to become reversed. The applied magnetic field must also precess at the rate (in synchronization) with the dipole. This is the resonance condition. If the external magnetic field is shut off, the protons 'relax'. The time required to reach their equilibrium (relaxed) state is called the spin-lattice relaxation time. The relaxation of the protons is sensed by measuring the voltage induced by the presessing dipoles.

For reasons not completely understood, relaxation of protons in confined fluids (fluids very near solid surfaces) is enhanced relative to relaxation in the bulk, free fluid. The response (voltage) measured on the polarizing coil of the nuclear magnetic log is called the free fluid index, it being thought that protons in fluids very near solid surfaces relax too quickly to contribute significantly to the signal. Because the nuclear magnetic log responds primarily to 'free' fluids, it has been used primarily for studies of permeability. Improved instrumentation and analyses procedures have permitted use for measurement of residual oil, gas identification, and analysis of heavy oil reservoirs (Neuman and Brown, 1982).Saraf (1970) used nuclear magnetic resonance techniques in the study of three phase relative permeabilities.

Waters contained in porous media at specific retention occupy the smallest pore space and are in close proximity to the solid surfaces. Thus, it is highly likely that the nuclear mgnetic log responds to a water content that excludes the water which would be held at specific retention. In other words, it seems that the free fluid index might be directly related to the specific yield as defined by Eqn. 3. It would be necessary, of course, to establish the relationship by correlation of the free fluid index with values of specific yield measured from cores. Certainly it seems probable that the free fluid index from the nuclear magnetic log would permit assessment of the drainable water in different strata relative to that of other strata. Such a relative index would be extremely helpful in the computation of drainable water over the entire aquifer thickness.

The fact that the relaxation time of protons depends upon their locations relative to solid surfaces has caused some workers to investigate the possibility of estimating pore-size distributions from nuclear magnetic measurements (Senturia and Robinson, 1970; and Loren and Robinson, 1970). Their method divides the total porosity into fractions or increments, each representing a different pore size range. The nuclear magnetic signal is analyzed to detect different relaxation rates corresponding to each increment of pore size. By this procedure, they were able to construct an approximate water retention curve from data from a nuclear magnetic log.

CONCLUSIONS

Three bore-hole geophysical methods were identified with potential applications to determination of specific yield of the confined, bedrock aquifers of the Denver Basin. Resistivity measurements, interpreted with consideration of the Waxman-Smits model for the influence of clays on formation resistivity, might prove to be valuable in establishing a cation exchange parameter which, in turn, might be related to specific retention. An independent determination of total porosity would be required, possibly by a combination of gamma attenuation and neutron scattering logs.

A second method identified is based upon down hole measurements of neutron lifetimes. Measurements of the rate of neutron capture are related to capture cross-sections of the rock matrix, 'free' water and 'bound' water. It is not clear how the 'bound' water in the dual water model is related to the specific retention, however. Furthermore, it is suspected that the neutron capture cross-sections of the very good quality water in the Denver Basin aquifers may be too small to permit this method. Essentially all experience with this method has been in formations containing waters with salinities far greater than those of the Denver Basin.

The nuclear magnetic log emerged as the technique with the most promise for assisting in the determination of specific yield. This log records a signal, called the free fluid index (FFI), that is thought to be proportional to the fraction of the total water that is not in close proximity to solid surfaces. Insofar as specific yield represents the drainable water in the larger pores, it seems likely that the FFI could be related directly and simply to specific yield. Even relative values (ratios) of FFI over the aquifer thickness would be very helpful in determining a properly weighted value for the drainable volume of water. For example, it is expected that the FFI would be very small in a shale or clay layer as compared to a clean sand and be indicative of the relative quantities of water that could be drained from each layer.

To the author's knowledge, the emphasis placed on interpretation of bore-hole geophysical measurements has always been directed toward something other than specific retention of specific yield. Thus, there exists a dirth of experience with the application of interest in this report. A carefully designed program of core collection, direct measurement, and bore-hole logging is required to establish the utility of the geophysical measurements for determining specific yield. The nuclear magnetic log appears to be the most promising in this regard.

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