GROUNDWATER RESOURCE EVALUATION

Walton

INTERNATIONAL
STUDENT
EDITION

GROUNDWATER RESOURCE EVALUATION

WILLIAM C. WALTON
Professor of Geology and Geophysics
Director, Water Resources Research Center
University of Minnesota

INTERNATIONAL STUDENT EDITION

McGRAW-HILL KOGAKUSHA, LTD.

Tokyo Auckland Düsseldorf Johannesburg London Mexico
New Delhi Panama São Paulo Singapore Sydney

To ELLEN, CYNTHIA, and LOUISE

GROUNDWATER RESOURCE EVALUATION

INTERNATIONAL STUDENT EDITION

KOSAIDO PRINTING CO., LTD. TOKYO JAPAN

PREFACE

During the last decade it has been more fully realized that refined quantitative answers are needed concerning available groundwater resources. Utilization of aquifers continues to accelerate to meet the needs for irrigation, industrial, urban, and suburban water supplies. As groundwater development intensifies, well owners become more interested in the response of aquifers to heavy pumping, whereas initially they were concerned largely with the delineation and exploration of aquifers. Competition for available resources has brought about an awareness that one of the principal problems confronting groundwater hydrologists is resource management. Before groundwater resources can be managed, they must be quantitatively appraised. In ever-increasing numbers, engineers, geologists, and others are being called upon to estimate how much groundwater is available for development and what will be the consequences of development. Groundwater users are continually asking for suggestions as to how available resources can be properly managed.

Proper planning for the development and management of groundwater resources requires the testing of all possible schemes and the appraising of the relative merits of various alternatives. Groundwater resource development and management personnel are concerned with the sustained yields of wells and aquifers, the interference between wells and well fields, the interrelation between surface water and groundwater, and the quality of groundwater. Questions pertaining to the use of groundwater resources require that pumping be related to water-level changes with reference to time and space. The hydrogeologic properties and dimensions of aquifers and existing aquitards and the boundaries of aquifers are of utmost importance in relating cause and effect. Cause cannot be related to effect until hydrogeologic maps are available. These maps must encompass all nonhomogeneous and irregular hydrogeologic conditions. Electric analog and digital computer techniques that allow the rapid study of cause-and-effect relationships involving complex aquifer conditions have recently been developed.

Along with the "information explosion" in the scientific world during recent years, there has been rapid and enormous progress in the science and technology concerned with groundwater. This progress has stimulated a great deal of interest, and correspondingly a large amount of research, among a widely diversified group of scientists. The ever-increasing scientific research on groundwater has resulted in a large body of knowledge which, for the most part, can only be found scattered through various scientific journals and technical reports, but in general is not easily accessible to many inquirers who wish to view all aspects of groundwater resource evaluation. It is highly desirable that the voluminous material in the groundwater resource evaluation field be assembled and briefed in order that engineers, geologists, and others actively engaged in quantitative studies can have available a ready reference.

My experience in teaching groundwater courses to engineers and geologists during the past several years has indicated the urgent need for a text which presents both the basic principles of groundwater resource evaluation and the practical application of techniques to well and aquifer problems. Derivation of equations as well as numerous illustrative case histories of analyses based on actual field data are presented in this book. Numerous practical problems which may be solved with available equations and methods of analysis are given. A comprehensive bibliography is presented containing references to the literature germane to groundwater resource evaluation that may be used to expand the reader's understanding of subject matter. The equations and analytical methods available to groundwater hydrologists are almost unlimited in number, and the discussion of all of them would necessitate several volumes and unwarranted duplications. A selection has therefore been made to include equations and analytical methods most frequently applied to actual groundwater resource evaluation field problems. The subject matter includes equations and methods used to quantitatively appraise the hydrogeologic parameters affecting the water-yielding capacity of wells and aquifers, and equations and methods used to quantitatively appraise the response of wells and aquifers to heavy pumping.

This book, in addition to serving as a text for groundwater courses, should aid in the systematic appraisal of groundwater resource problems by practicing engineers and geologists. Graduate students should be stimulated by the broad perspective of groundwater resource evaluation.

WILLIAM C. WALTON

CONTENTS

CHAPTER 1

INTRODUCTION

Groundwater is one of the earth's most widely distributed and most important resources. Groundwater exists wherever water penetrates beneath the surface, the rocks beneath the surface are permeable enough to transmit this water, and the rate of infiltration is sufficient that the rocks are saturated to an appreciable thickness. These conditions are met and groundwater exists at least intermittently in a very large part of the United States. Groundwater becomes a usable resource when the rocks in the zone of saturation are permeable enough to yield useful supplies of water to wells, springs, or streams; when the zone of saturation is perennial, or at least persists long enough each season to allow practical exploitation; and when the mineral substances dissolved by the water as it percolates through the soil and rocks do not reach such concentrations as to make the water unfit for the desired use. At least the small quantities of potable water needed for domestic supply are available very widely. Only where impermeable or saline rocks or permanently frozen ground extend to great depths or where the climate is exceedingly dry, or on an island too small or too permeable to retain useful supplies of water, is potable groundwater entirely or practically absent; even in large regions having these general characteristics, groundwater may be available locally.

While the pattern of surface-water flow is generally known and the potentials of surface-water reservoirs on principal rivers have been extensively appraised, there has been only limited study of the nation's groundwater resources. Groundwater studies to date have been predominantly in problem areas and have been largely concerned with falling groundwater levels, failure of wells, or impairment of groundwater quality. Recent studies have added to the knowledge of the geographical distribution of the nation's groundwater resources and have provided the base for rough estimates of the magnitude of undeveloped potentials. More detailed studies in limited areas have clarified a few of the complex features of groundwater reservoirs. The determination and appraisal of groundwater resources is slow and time-consuming work. Although the general geologic and groundwater conditions throughout the United States are known, the detailed information necessary for meaningful quantitative estimates of groundwater resources is known only for a small part of the country.

Groundwater's importance to the nation is not fully appreciated. Groundwater accounts for only a fifth to a sixth of the total amount of water withdrawn from all sources. But, its place in the nation's economy is not be be measured solely by the ratio of groundwater withdrawn to surface water withdrawn. For example, groundwater is more widely and easily available than surface water, and most groundwater is unpolluted and relatively safe from pollution. About one-third of the conterminous United States is underlain by groundwater reservoirs generally capable of yielding at least 50 gallons per minute of water per well. There are large areas where hundreds or even thousands of gallons per minute can be obtained from wells. Groundwater generally averages out to be a little harder and more mineralized than surface water in the same locality, but its quality is more uniform during the year. It is rarely if ever necessary to consider removal of sediment from groundwater. Where groundwater is polluted, treatment to make it safe is simple and relatively inexpensive. Groundwater is the practical source of emergency supplies in the event of a national nuclear disaster. The temperature of groundwater, like its chemical quality, is relatively uniform throughout the year. This makes it preferable for cooling purposes in the summer, when surface water is warmer. Groundwater enabled the settlement and continued occupation of our agricultural areas and furnished public and industrial water for most of the towns and cities that grew up around the country. Groundwater is still an underdeveloped resource in large areas, is contributing substantially to our industrial growth, and is the most practical source for supplemental irrigation.

Groundwater reservoirs accept water; they filter it to remove sediment and disease-causing organisms; they store it in quantities vastly exceeding those which are or conceivably could be stored in all natural and artificial surface-water bodies put together; they even out its temperature and chemical quality; they transport it from areas of replenishment to areas of need; and they slow down its natural discharge to the surface so that it makes up the bulk of the dry-weather flow of streams. To an increasing extent they will be used to store surplus surface water through artificial recharge. This practice will have a benefit in reducing floodflows and flood damage, but its greatest value will be in reducing the waste of good-quality water which otherwise serves no useful purpose.

Water and the materials over and through which groundwater flows constitute a vast, complex dynamic system in which any change in the operation of one part is reflected in more or less substantial changes in other parts. In analyzing groundwater systems, consideration must be given to the effect groundwater withdrawals will have on such things as the water levels in nearby wells or in a wetland, the flow of contaminants or salt water toward wells, and the reduction of flow in a nearby stream. The pumping may serve a desirable purpose, but it may be desirable also to maintain the flow of the stream to dilute wastes, to preserve the wetlands as a habitat for wildlife, or to protect the well itself or other wells from salt-water encroachment. The need is to understand cause-and-effect relationships well enough to be able to describe a series of possible alternative development and managment choices and the consequences of each. For full development of groundwater reservoirs, groundwater's place in the hydrologic cycle and in hydrologic systems must be evaluated and the groundwater resource must be described quantitatively rather than just in qualitative terms. Adequate data and imagination, uncircumscribed by disciplinary boundaries, can lead to vast improvement in the efficiency of groundwater use. Conjunctive use and management of surface water and groundwater multiplies the number of alternatives available for water management because it multiplies the times, places, and means for water development and the number of circumstances under which development can be accomplished.

1.1 Hydrologic Cycle

The chain of events describing the history of water is called the *hydrologic cycle*. The cycle involves the total earth system: atmosphere, hydrosphere, and lithosphere. The atmosphere is the gaseous envelope above the hydrosphere, the hydrosphere consists of the bodies of water that cover the surface of the earth, and the lithosphere is the solid rock environment below the hydrosphere. The cycle of activities of water extend through these three parts of the earth system from an average depth of at least a half mile in the lithosphere to a height of about 10 miles in the atmosphere.

In the hydrologic cycle, water evaporates from the oceans and the land and becomes a part of the atmosphere. The evaporated moisture is lifted and carried in the atmosphere until it precipitates to the earth, either on land or in the oceans. The precipitated water may be intercepted or transpired by plants, may run over the ground surface and into streams to oceans, or may infiltrate into the ground. Much of the intercepted and transpired water and some of the surface runoff return to the air through evaporation and transpiration. The infiltrated water may percolate downward to be temporarily stored as groundwater which later flows out of rocks as springs, or seeps into streams as runoff to oceans, or evaporates into the atmosphere to complete the cycle. Thus, the hydrologic cycle undergoes various complicated processes of evaporation, precipitation, interception, transpiration, infiltration, percolation, storage, and runoff. Figure 1.1 illustrates the hydrologic cycle.

The hydrologic cycle reaches into the atmosphere and traverses the domains of hydrometeorology, meteorology, and climatology. In the hydrosphere, it crosses, or embodies, the domains of potamology (surface streams), limnology (lakes), cryology (snow and ice), glaciology, and oceanology. In the lithosphere, the hydrologic cycle relates to agronomy, hydrogeology (emphasizing geologic aspects), geohydrology (emphasizing hydrologic aspects), and geomorphology. As water affects plants as well as animals, the hydrologic cycle extends itself into plant ecology, silviculure, biohydrology (emphasizing hydrologic aspects), and hydrobiology (emphasizing biologic aspects). The cycle has its important influence in agriculture, forestry, geography, watershed management, political science (water law and policy), economics (hydroeconomics), and sociology; and it has practical applications in structural design, water supply, waste-water disposal and treatment, irrigation, drainage,

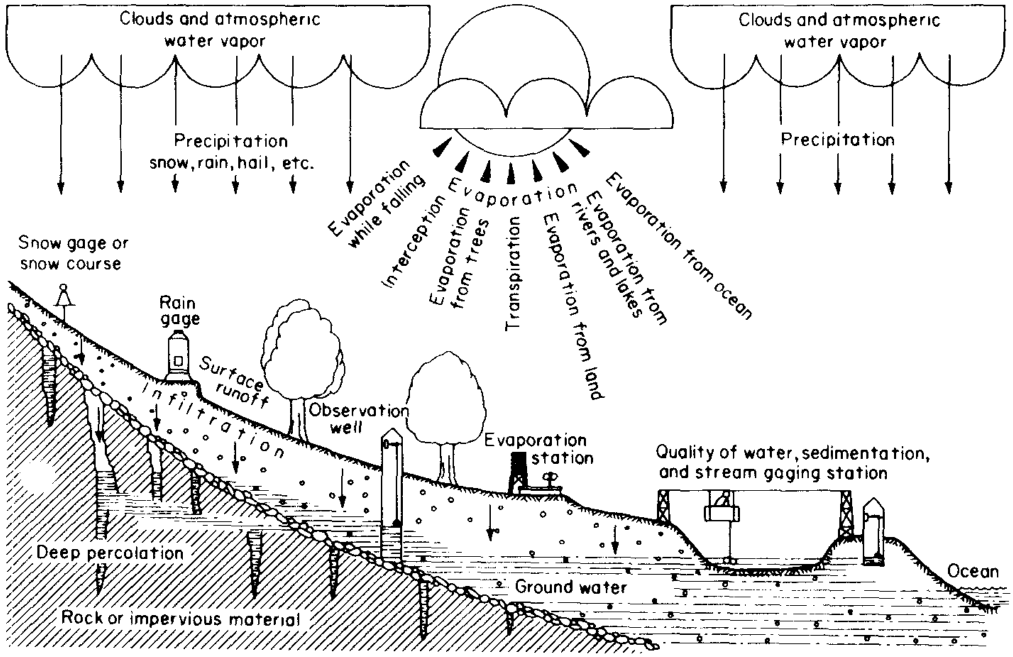

Fig. 1.1 Diagrammatic representation of the hydrologic cycle. (*Adapted from ASCE Hydrology Handbook, 1949.*)

hydropower, flood control, navigation, erosion and sediment control, salinity control, pollution abatement, recreational use of water, fish and wildlife reservation, insect control, and coastal works.

The amounts of evaporation, precipitation, runoff, and other hydrologic cycle quantities are not evenly distributed on the earth, either geographically or time wise. In the conterminous United States, annual rainfall averages 1,430 cubic miles; evaporation is about 1,000 cubic miles; discharge of water to the oceans from surface streams is about 390 cubic miles; and about 40 cubic miles of water is discharged directly into the oceans from groundwater reservoirs (Nace, 1965). Several times 40 cubic miles of water passes through inland groundwater reservoirs and reaches stream channels to be discharged to the oceans via surface streams.

That part of the hydrologic cycle that occurs beneath the land surface, and that is therefore invisible, is surrounded with misunderstanding and misconceptions. Groundwater is regarded by a great many people as being no less mysterious than it appeared to our forebears of the Middle Ages, who often explained it by means of supernatural phenomena. Many still feel that the occurrence of groundwater, its replenishment, movement, and discharge, is so strange as to defy scientific explanation; they feel that groundwater can be understood and located only by persons who are supposedly possessed of occult powers (water dowsers) or by the use of instruments whose operations are as mysterious as their operators. The puzzling and apparently mysterious complexity of the occurrence and movement of groundwater is largely the result of the complex geologic history of our earth. It results from the fact that our continent, which now appears so stable and permanent, has been subjected during eons past to uplift, then erosion, sedimentation and folding and faulting, deep-seated intrusions of molten rocks and surficial outpourings of lava, invasions of the land areas by the sea, and burial under huge masses of glacial ice advancing from the mountains or the frigid north.

The geologic history through which any particular area has passed very largely influences the hydrologic cycle in that area. If the history has been such as to form layers of sand, the soil probably will readily absorb rainfall, and there will be a minimum of runoff over the land surface. The streams will reach flood stages only during very heavy storms and they will tend to have a uniform, steady flow even during dry-weather periods. Drilled or dug wells probably will produce large amounts of water. On the other hand, if the history has been such that subsurface materials are dominantly clay or silt, the soil will absorb water with difficulty. Storms of relatively small magnitude will cause substantial overland runoff. The streams will flood frequently and will tend to dry up during even moderate droughts. Wells will produce relatively little water, and in some places none at all. Inasmuch as the geologic history is infinitely varied in different parts of the country, the number of variations to the simple examples cited is likewise infinite.

1.2 History of Groundwater Resource Evaluation

Many centuries were required to establish the hydrologic cycle concept. The solution of the problem of the origin of groundwater contributed to the development and slow acceptance of the concept (see Parizek, 1963). According to Keilhack (1912), the origin of groundwater was mentioned in Book 21 of Homer's *Iliad*, written about 1000 B.C., as follows: "with Zeus neither does the mighty river Achelous fight nor the mighty strength of the deep-flowing Oceanus, from which flows all rivers and every sea and all springs and deep wells." Herodotus (484–425 B.C.) reasoned that the sun "attracts the water. After attracting it [the sun] again repels it into the upper regions, where the winds lay hold of it, scatter it, and reduce it to a vapor." Before the sun again returns to its summer position in the sky "the other rivers run big, from the quantity of rainwater which they bring down from countries where so much moisture falls that all the land is cut into gullies; but in summer, when the showers fail, and the sun attracts their water, they become low" (Herodotus, *Persian Wars*).

Anaxagoras (500–428 B.C.) recognized the importance of evaporation and rainfall as a source of water for rivers, but thought in terms of great reservoirs probably of the Tartarus vast-cavern type. Anaxagoras also recognized the importance of rainfall, recharge, and underground storage even though he incorrectly understood the nature of this storage.

Plato wrote in *Critias*, around 350 B.C., about the rainfall-runoff segment of the cycle, the infiltration of surface water and underground storage segments, and made correct statements concerning the origins of springs and streams. Aristotle (384–322 B.C.) recognized the cyclic path of water between land and air, evaporation and condensation and their importance in rainfall, and that some rain is discharged by streams, while some percolates into the earth and reappears in springs (*Meteorologica*). The importance of evaporation, rainfall, and infiltration to the origin of groundwater was clearly and correctly stated by Vitruvius, who lived at the time of Christ (Vitruvius, *Architecture*).

Leonardo da Vinci recognized artesian underground systems. Bernard Palissy (1509–1589) correctly explained the relationship between wells and rivers, the origin of springs and rivers, the hydrologic cycle, and changes in water levels in wells (Palissy, *Discours Admirables*). Pierre Perrault (1608–1680), a French scientist, demonstrated that rainfall is more than adequate to account for the discharge of rivers and springs. His work was extended some years later by another French scientist, Mariotte (1620–1684), who correlated seepage into a cellar with rainfall and showed that the flow of springs varied according to rainfall and that infiltration of rainfall supplied springs and wells with their water. In 1693 Edmund Halley (1656–1742), a British astronomer, demonstrated that evaporation was ample to supply the quantity of water returned to the sea by rivers flowing into it. Bernardino Ramazzini gave an accurate account of the origin of artesian pressure in 1691. Vallesiere (1715) recognized the importance of an impermeable stratum to serve as a confining layer to an artesian system. La Metherie in 1791 explained that a part of the water from rain and snow flows off directly, a second part moistens the soil and evaporates or feeds the plants, and a third part penetrates to subsurface reservoirs at greater depths, from which it gradually issues as springs.

The series of developments between 1856 and 1955 which helped to establish the principles of groundwater resource evaluation as a quantitative science were described by Ferris and Sayre (1955). Darcy (1856) did experimental work on the flow of water in sands and derived a formula known as Darcy's law, which expresses the relationship between velocity of percolation, permeability of water-yielding materials, and the hydraulic gradient. Darcy's law serves as the basis for numerous quantitative methods in groundwater resource evaluation. Dupuit (1863) was the first scientist to develop a steady-state formula for the flow of water into a well. A. Thiem (1870) developed equations for flow toward wells and galleries. Forchheimer (1886) introduced the concepts of conformal mapping and the construction of flow nets, the method of images, and the theory of functions of the complex variable. He was the first to solve the problem of groundwater flow in a semi-infinite water-yielding formation bounded by a perennial stream and the problem of a well discharging from a water-yielding formation that is supplied by uniform recharge. Badon Ghyben (1889) established the laws of equilibrium between sea water and fresh groundwater. Slichter (1898) showed the relationship between grain size of rocks and permeability, and the motion of groundwater. Chamberlin (1885) defined the requisite geologic controls necessary to the occurrence of artesian wells. Detailed information on the relation of head to groundwater movement was presented by King (1892).

Turneaure and Russell (1901) published a textbook on public water supplies, which included their counterpart of Thiem's and Slitcher's equations for radial flow toward a discharging well. G. Thiem (1906) developed a field method for determining permeability of water-yielding formations and the rate of flow of water, using a pumping well and the resultant drawdown in observation wells. Horton (1906) extended the steady-state formulas of Slichter to provide a method for determining the proper depth and spacing of tile drains. Meinzer (1923) evaluated early studies on the framework of principles and methodology for investigations of the occurrence and distribution of groundwater and provided the first manual for groundwater hydrologists.

The water-logging of lands was investigated by Gardner et al. (1928), Israelsen and McLaughlin (1935), and Kirkham (1945), who analyzed the hydraulics of flow toward drains overlying artesian water-yielding formations. The work of Hopf and Trefftz (1921), Pavlovsky (1922), Kozeny (1933), Lindquist (1933), Hamel (1934), Muskat (1935), Verdernikov (1934), Meleschenko (1936), and Vreedenburgh and Stevens (1936) greatly expanded the development of solutions for two- and three-dimensional flow toward canals and drains.

De Glee (1930) provided a solution to the problem of a steady flow toward a well in a leaky artesian water-yielding formation replenished by an overlying water-yielding formation. Lewis (1932) provided the first practical solution for steady radial flow to a well in a water-yielding formation receiving steady, uniform recharge. The distribution of potential about a partially penetrating well was analyzed by Forchheimer (1930), Kozeny (1932), Muskat (1932), and Hantush (1964). Methods for determining the entrance losses in a pumped well were described by Kano (1939), Jacob (1947), Rorabaugh (1953), and Engelund (1953). Methods for estimating groundwater recharge or discharge from changes in groundwater storage were devised by Smith (1924), White (1932), Meinzer (1928), and Williams and Lohman (1949). One of the most important milestones in the development of groundwater resource evaluation was Theis's (1935) introduction of an equation for the non-steady-state flow to a well.

Sand-tank models were applied to radial-flow problems by Wyckoff et al. (1932), Babbitt and Caldwell (1948), Hansen (1952), Childs et al. (1953), Kozeny (1932), Muskat (1935), Vaidhianathan et al. (1934), Baumann (1951), and Day and Luthin (1954). Spaced-plate or viscous-flow models were used by Dietz (1944), Moore (1949), and Zanger (1953). Electric analog models were developed for the solution of complex flow patterns by Muskat (1935), Babbitt and Caldwell (1948), Wyckoff et al. (1933), and Zanger (1953).

Streamflow records were analyzed to determine recharge to the groundwater reservoir and discharge of groundwater to streams by Mendenhall (1905), Piper (1939), Houk (1921), and Meinzer (1928). Muskat (1937) published a comprehensive text on fluid flow through porous media. The use of the method of images and Green's functions were developed and solutions were presented for semi-infinite, quarter-infinite, and infinite-strip water-yielding formations. The hydraulics of groundwater flow toward wells in reentrants, buried channels, horst and graben structures, and other geologic situations was clearly developed.

Theis (1937) formulated the first transient-state flow of groundwater to a discharging ditch or drain. Kirkham (1945), Childs (1945), and Engelund (1951) provided thorough analyses of the flow of groundwater and soil water toward drains.

Hubbert (1940) derived from the Navier-Stokes equations Darcy's law and introduced the concept of force potential in his mathematical derivation. Hubbert (1940) pointed out the physical principles of the fresh-water–salt-water relationship for the hydrodynamic condition. Jacob (1940) clarified quantitatively the storage coefficient as it applies to the elastic artesian water-yielding formation. Several useful corollary equations were developed from the Theis formula by Theis (1935) and Jacob (1950). Guyton (1941) demonstrated that drawdowns computed with the Theis formula checked closely with actual field observations. Mathematical analyses of groundwater flow on a basin-wide scale were made by Hubbert (1940), Jacob (1945), Steggewentz (1933), Werner and Noren (1951), and Ferris (1951). Subsidence of land due to groundwater withdrawals was investigated by Tolman and Poland (1940). Methods for treating river-water infiltration to streamside wells were presented by Theis (1941), Rorabaugh (1951), Hantush (1964), Kazmann (1948), and Walton (1963). The application of Theis's formula and the method of images for locating water-yielding formation boundaries was described by Ferris (1948). Methods for analyzing data on water-level interference resulting from operation of several wells were developed by Wenzel and Greenlee (1943) and Cooper and Jacob (1946). More comprehensive analyses of the leaky artesian problem were added by Jacob (1946) and Hantush (1964). Jacob (1946) formulated transient-state solutions for a well in a leaky artesian situation and for a well of constant drawdown in an elastic artesian situation.

Principles of cation exchange were described by Piper et al. (1953) and Love (1944). Base exchange in groundwaters was studied by Renick (1925) and Poland et al. (1948). Quantitative methods for the study of the influx of mineralized waters in areas of intensive pumping were developed by Hill (1942), Langelier and Ludwig (1942), and Piper (1944).

Detailed discussions of the use of numerical methods for solving problems involving flow in aquifers were given by Yang (1949), Boulton (1951), Kashef et al. (1952), Luthin and Scott (1952), Shaw and Southwell (1941), and Stallman (1955).

The quantitative relationship between water quality and electrical resistivity was developed and used by Jones and Buford (1951). Hansen (1952) and Zanger (1953) used mechanical (elastic) models to solve groundwater problems. Stuart et al. (1954) analyzed groundwater problems associated with iron-ore mining. Hubbert (1953) presented new concepts relating to the entrapment of petroleum and groundwater conditions. Ahrens (1957) presented well-design criteria. Hem (1959) summarized methods for interpretation of chemical characteristics of natural water. Henry (1959) and Bear and Dagen (1963) derived equations concerning salt-water intrusion into fresh-water aquifers. Kohout (1960) presented data on the cyclic flow of salt water in coastal water-yielding formations. Hydrodynamic dispersion and mixing of water in aquifiers was analyzed by Bear (1961).

Koenig (1960) analyzed economic aspects of water-well stimulation. Rasmussen and Andreasen (1959) and Schicht and Walton (1961) prepared hydrologic budgets for basins. Back (1961) presented techniques for mapping hydrochemical facies. Skibitzke (1961) applied electric analog techniques to solving complex groundwater system problems. Walton and Prickett (1963) extended the application of analog techniques in solving complex groundwater system problems. Walton and Neill (1961) analyzed groundwater problems with a digital computer. Poland (1961) described the coefficient of storage in a region of major subsidence caused by compaction of water-yielding formations. Lusczynski (1961) derived equations for the head and flow of groundwater of variable density. Patten and Bennett (1963) summarized applications of electrical and radioactive well logging to groundwater hydrology. Sniegocki (1963) summarized problems in artificial recharge through wells. Toth (1963) provided a theoretical analysis of groundwater flow in small drainage basins. Walton and Neill (1963) analyzed specific-capacity data to determine the hydraulic properties of water-yielding formations. Boulton (1963) devised a method for analyzing pumping tests under water-table conditions which was extended by Prickett (1965). Cooper and Rorabaugh (1963) analyzed groundwater movements and bank storage due to flood stages in surface streams. Hantush (1964) provided solutions for many well-hydraulics problems, including those associated with leaky artesian conditions, partially penetrating wells, induced infiltration of streamflow, and horizontal collectors. Walton et al. (1967) analyzed with electric analog computers recharge from induced streambed infiltration under varying groundwater-level and stream-stage conditions.

Forced by the necessity of solving pressing groundwater supply problems, most recent advances in groundwater resources evaluation have dealt with water-well hydraulics and well-field designs. The most striking trend in 1968 was the renewed interest in Darcy's law and all aspects of regional groundwater flow, as opposed to the previous preoccupation with hydraulics of water wells and well fields. In 1968, groundwater hydrologists were concerned with whether Darcy's concept of groundwater motion can be extended and how much further it can be applied. This trend manifests itself in two ways: on the one side are studies pertaining to the explicit validity of Darcy's law, in which special attention is given to the exact meaning of the permeability constant, and the meaning of hydraulic head and of hydraulic gradient. On the other side are attempts to apply Darcy's law in a much wider sense, whereby it is assumed that the law is valid for all natural conditions of groundwater flow. In this respect particular attention is being paid to the laws that govern the regional distribution of hydraulic head. Finally, the question of whether there are other laws that govern groundwater motion is being investigated.

During the 1960's, there has been a tremendous increase in knowledge with regard to hydrodynamic flow systems. Groundwater–surface-water relationships received more attention as hydrologists increasingly adopted the "systems analysis" point of view in attempting to visualize the effects throughout whole hydrologic systems of various water development and management projects. Some fundamental work was accomplished on induced infiltration from streams to wells, on filling and emptying of "bank storage" as a result of natural fluctuations in stream storage, on analysis of water-level fluctuations in wells resulting from tidal and other changes in stream storage in terms of water-yielding formation characteristics, and on interchange of fresh and saline water between coastal water-yielding formations and the ocean.

Geophysical methods are being used increasingly in groundwater studies. Prospecting by the electrical-resistivity and seismic methods has been supplemented on a small scale by magnetic and gravity surveys. "Borehole geophysics," however, was the principal tool in 1968. The chief advances have been in neutron and gamma-ray logging, in the hydraulics of multiple-aquifer wells, and in textural and geochemical interpretations from resistivity and spontaneous-potential data. Borehole geophysics is expected to be a principal tool in getting more reliable information at practical cost from wells and test holes in the construction of analog models of groundwater systems.

There has been an increasing emphasis on regional or basin analysis of groundwater systems. Electrical analog models employing the analogies between resistors and permeability and between capacitors and storage coefficient have been developed to the stage where they can be used routinely on areal studies as simulation models of groundwater systems. New techniques for automated data processing using the digital computer now offer the opportunity for organized storage and retrieval of the vast quantities of groundwater data that are presently available, and, in addition, they provide means for computing and compiling the data into printout tables, graphs, and maps. The use of simulation models, either analog or digital, for analysis of groundwater systems has required field studies attempting to quantify geology by trying to relate various geologic factors to such characteristics as the magnitude and distribution of permeability.

The subjects of effects of urbanization, salt-water encroachment, brackish groundwater, corrosion of well casings, use of specific-capacity data for estimating transmissibility, subsidence, and artificial recharge were receiving considerable attention in 1968.

1.3 Needed Research

Much valuable groundwater research has been accomplished and is now underway. However, intensified interest and demand for knowledge of groundwater resources calls for continuing additional effort. Several professional society committees have studied and reported on groundwater research needs. Some of the subjects mentioned in committee reports are listed in the hope that this will stimulate thought and additional research in groundwater resource evaluation.