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Simulation and Analysis of Stream-Aquifer Systems

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SIMULATION AND ANALYSIS
OF
STREAM-AQUIFER SYSTEMS

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By

Morton W. Bittinger

Fort Collins, Colorado

A dissertation submitted in partial
fulfillment of the requirements for the
degree of Doctor of Philosophy in Civil
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Morton W. Bittinger

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ABSTRACT

Simulation and Analysis of Stream-Aquifer Systems

by

Morton W. Bittinger, Doctor of Philosophy
Utah State University, 1967

Major Professor: Dr. Calvin Clyde
Department: Civil Engineering

As defined for this study, a stream-aquifer system is a hydrologic system in which there is an intimate hydraulic interrelationship between one or more aquifers and a perennial stream. The objectives of this study are to better understand the response behavior of typical stream-aquifer systems, to look at the response behavior as influenced by water management practices, and to consider the problems and possibilities of integrated management of groundwater and surface water supplies within stream-aquifer systems.

A brief history of water development practices and policy, particularly in the Western United States, indicates that the tendency over the years has been to attempt to improve efficiency of use and increase water availability by means of coordinated management of sources and uses of water within hydrologic units. This tendency is manifested by the concepts of "basin planning," "multiple purpose projects," and "comprehensive planning." Also, history shows that surface and groundwater have typically been developed separately with little regard for the interrelationships between the two.

Through the cooperation of the U.S. Geological Survey, major stream-aquifer systems in the Western United States have been identified. The Soil Conservation Service provided information on water management problems, causes, and needs found within the major stream-aquifer systems. Components of stream-aquifer systems are classified into (1) input variables, (2) system parameters, (3) output or system responses. Techniques for modeling stream-aquifer systems are discussed, and the mathematical model technique used is presented.

Over 160 stream-aquifer systems were simulated, utilizing mathematical models and digital computer solutions. The response behavior was measured in terms of the change of groundwater levels and the pattern of outflow to the stream. The latter system response is emphasized because of the effect upon other water users which is often not considered when changes are made in water management practices. The influence of such variables and parameters as (1) the total water added to the aquifer, (2) the time distribution of the water added, (3) the areal distribution of the water added, (4) the aquifer hydraulic characteristics, (5) the geometric characteristics of the aquifer, and (6) the initial configuration of the water table surface are discussed with results presented in tabular and graphical form.

The effect of common water management practices (drainage, phreatophyte control, improvement of irrigation efficiency, and lining of canals), along with further water management practices desirable in a fully integrated stream-aquifer system are discussed.

INTRODUCTION

The ever-increasing demands upon the Nations' water supplies present a substantial challenge to water researchers, educators, administrators, and legislators, as well as to the public in general. The more spectacular and glamorous aspects of this challenge include the possibilities of large-scale continent-wide transport of water from water-rich to water-poor areas and the possibilities of increasing water supplies through weather modification and saline-water conversion. Although these aspects command greater public attention, the fundamental challenge to the majority of workers concerned with water is that of increasing the beneficial use of existing sources of supply through improved efficiency and integrated management.

History of Water Development

In many regions of the arid west, the era of development of new water supplies is rapidly drawing to a close. Problems of managing supplies are necessarily related to physical, social, and legal aspects of the developmental period. Therefore, a brief discussion of historical development of water is given as an introduction to the main theme of this treatise.

Initial development of surface water

The initial pattern of water development was typically haphazard and spotty. In general, the sources and locations in which water could be most easily converted from natural conditions to a usable state were developed first. Initially, the developments were through the efforts and financing of individuals and small groups. In the Western States, this phase of surface water development occurred generally between 1860 and 1900. During this period groundwater development occurred on a very minor scale, being prior to any extensive exploration or knowledge of aquifers and the development of advanced technology related to well construction, pumps, power units, and power supplies.

Large-scale storage and conveyance facilities

As development of surface-water supplies progressed and uses increased, the need for stream-flow regulation became apparent. Flows during the spring and other high-runoff periods were greater than could be utilized, whereas supplies were often insufficient during peak-use and low-runoff periods. Thus, the late 1800's and early 1900's became a period in which large-scale storage and conveyance facilities were constructed. The greatest impetus to this era came with the Reclamation Act of 1902 and subsequent amendments which provided for Federal financial and technical assistance in the design and construction of large-scale water projects.

Basin-planning and multiple-purpose concepts

The earlier surface-storage reservoirs were generally designed and constructed for a single purpose. As competition for water supplies increased, the "basin-plan" and "multiple-purpose" concepts evolved as a means of achieving greater efficiency in water development and use. These concepts inferred the inclusion of more than one water use and consideration of a larger portion of society's needs in the design of projects.

The Tennessee Valley Authority Act of 1933 initiated the first large-scale treatment of a river basin as a unit for the planning and development of water resources. Multiple-purpose projects began receiving attention upon passage of the Flood Control Act of 1936 and subsequent legislation authorizing the Army Corps of Engineers and the Bureau of Reclamation to construct projects serving flood control, irrigation and power purposes. More recent legislation and government policy statements such as the well-known Senate Document 97 (U.S. Senate, 1962) explicitly set forth the various purposes and benefits which must be considered in the planning and cost allocation of Federally financed projects.

Concurrently, during this period, efforts to conserve and protect soil and water resources through vegetative management and upper watershed treatment became prominent. The Soil Conservation Act of 1935 created the Soil Conservation Service within the Department of Agriculture. This agency and the research arm of the Department of Agriculture, the Agricultural Research Service, have devoted considerable effort toward improving the efficiency of water utilization in agriculture.

Groundwater development period

Large-scale development of groundwater supplies generally began in the 1930's with the advent of rural electrification and improved vertical-turbine pumps. Favorable agricultural prices and drouth conditions contributed to another surge in the 1950's. MacKichan (1961) estimated over 51 million acre-feet of groundwater were withdrawn in the United States in 1960. Irrigation was the largest user of groundwater (34 million acre-feet) with the states of California, Texas and Arizona accounting for about two-thirds of the irrigation usage (21.4 million acre-feet) and over one-half of the total groundwater withdrawn (over 26 million acre-feet).

With few exceptions, groundwater development has been accomplished through private initiative and investments. During the initial stages of development within an area, irrigators and others using large quantities of groundwater generally enjoyed an independence and flexibility rarely available to surface-water users. As numbers of wells increased, with accompanying increases in quantities of water withdrawn, problems of interference, depletion, impaired quality, etc., have arisen which cannot be solved by individual action alone. This has resulted in movements to organize into groundwater districts (Smith, 1956, 1962; Smith and Bittinger, 1964) and other well-users associations.

Comprehensive planning

Now, in the 1960's, the increasing pressures for better management and higher efficiency of water use have resulted in what many refer to as the "comprehensive plan" of development and use. Whereas the multiple-purpose concept was primarily concerned with the uses to which a particular source of water was to be put, the comprehensive plan infers a broader concept applied to entire basins and to several established and potential uses and sources. However, as pointed out by the U.S. Senate Select Committee on National Water Resources, the term has not been used as broadly as many desire:

> ... The concept of comprehensive development should be redefined to include all purposes served by water resources and all measures available for meeting prospective demands, including the preservation and improvement of water quality, instead of limiting this definition to the mere volumetric management of surface water resources, which has generally gone under the term of "comprehensive development" in the past ... (U.S. Senate Select Committee, 1961, p. 45).

The implementation of conjunctive use and integrated management plans has been slow, partly because the operational characteristics of groundwater basins have not been fully understood. The U.S. Senate Select Committee on National Water Resources recognized this need:

> ... as one facet of comprehensive planning for the development of water resources, there is need for developing information which will help in improving the use of groundwater and integrating its use with the use of surface water. (U.S. Senate Select Committee, 1961, p. 58).

Scope and Objectives

This treatise is an attempt to contribute to the knowledge necessary for implementation of the integrated management of groundwater and surface water supplies. Its scope is limited to a specific type of hydrologic system referred to as a "stream-aquifer system." This term, as used herein, refers to a single, watercourse, unconfined alluvial aquifer and an overlying hydraulically connected perennial stream. In such a system, the use of water from the stream or the aquifer influences the space and time distribution of water in the other source. Stream-aquifer systems in the Western United States in which irrigation constitutes the major use of water are emphasized.

The primary objectives of this study are:

1. To study the operational behavior of typical stream-aquifer systems as influenced by system parameters.
2. To determine the sensitivity and type of response of stream-aquifer systems to changes in water-management practices.

Secondary objectives pursued to provide background information and to achieve the primary objectives are:

1. To determine the location and extent of the major stream-aquifer systems in the Western United States.
2. To determine the types of water management problems, causes, and needs within these major stream-aquifer systems.
3. To review methods of describing stream-aquifer systems (e.g., from geomorphologic, hydrologic, hydraulic, etc., standpoints) and determine the pertinent components of stream-aquifer systems to quantify in order to meet the primary objectives.

4. To discuss and analyze the applicability of various simulation techniques for modeling the hydraulic interrelationships of stream-aquifer systems.
5. To discuss the potentials and problems of implementing integrated management of groundwater and surface water within complex stream-aquifer systems.

The first four of the secondary objectives are covered in the following three sections: "Stream-Aquifer Systems in the Western United States," "Description of Stream-Aquifer Systems," and "Simulation Techniques." The fifth is covered in the section titled "Stream-Aquifer System Behavior"--the section which also covers the primary objectives.

Conjunctive use and integrated management

The conjunctive use of surface and groundwater storage facilities has been advocated as a practice which may improve the efficiency of water use. Many prominent hydrologists and organizations (including Conkling, 1946; Banks, 1953; Thomas, 1955; Todd, 1959; and the ASCE Committee on Groundwater, 1961) have discussed the potentials of conjunctive use in general terms. Clendenen (1954) applied the concept to the U.S. Bureau of Reclamation's Folsom Project in California. He showed that water utilization could be increased from 51 percent to 82 percent of the average basin runoff by the planned operation of a groundwater reservoir in conjunction with the project's surface water reservoir. One of the largest conjunctive use projects is outlined in the California Water Plan (State of California, Department of Water Resources, 1957). This plan contemplates the utilization of 31 million acre-feet of groundwater storage capacity within the Central Valley in conjunction with surface storage facilities.

The term "integrated management" of surface water and groundwater generally carries a slightly different connotation than the term "conjunctive use." The integrated management concept is usually applied to situations in which the two supplies have already been fully developed by many separate and independent--but often conflicting and overlapping--interests. The integration of these supplies and interests into one management or administrative unit requires not only a thorough understanding of the interacting hydrologic and hydraulic factors, but also full recognition of vested legal rights, financial investments in facilities, and established organizations.

STREAM-AQUIFER SYSTEMS IN THE WESTERN UNITED STATES

Figure 1, adapted from Thomas (1951, Plate I), shows approximately 175 reaches of rivers and streams in the conterminous 17 Western States identified as "watercourse" aquifers. Thomas referred to these as comprising one of three types of aquifers classified according to the kind of problems encountered in development and use of groundwater. His designation corresponds to the term "stream-aquifer system" used herein as evidenced by his description of a watercourse aquifer:

> 1. It is a geologic unit comprised of materials of varying textures and permeabilities all deposited by the stream.
> 2. It is a hydrologic unit, in which both surface water and groundwater are moving toward the same general destination.
> 3. The watercourse may cross other groundwater reservoirs, in which case the other reservoir may discharge water into the groundwater reservoir and the stream of the watercourse, or vice versa, depending upon the hydraulic gradient.
> 4. In the watercourse, the impermeable bed provides no more than local isolation of surface water from groundwater, or of the water in individual aquifers of the groundwater reservoir. In general, there is intimate relationship to the extent that water traveling in the watercourse may be classed successively as groundwater, surface water, and "diffused surface water" (Thomas, 1951, p. 136-7).

Stream-aquifer systems, or watercourse aquifers, exist within all the major river basins of the United States. In general, those of the Western States present more problems for integrated management because of over-appropriated surface-water supplies, recharge of groundwater and return flow as a result of the use of surface water for irrigation, and erratic seasonal and annual runoff patterns.

In order to obtain information on stream-aquifer systems in the Western States, the writer contacted each

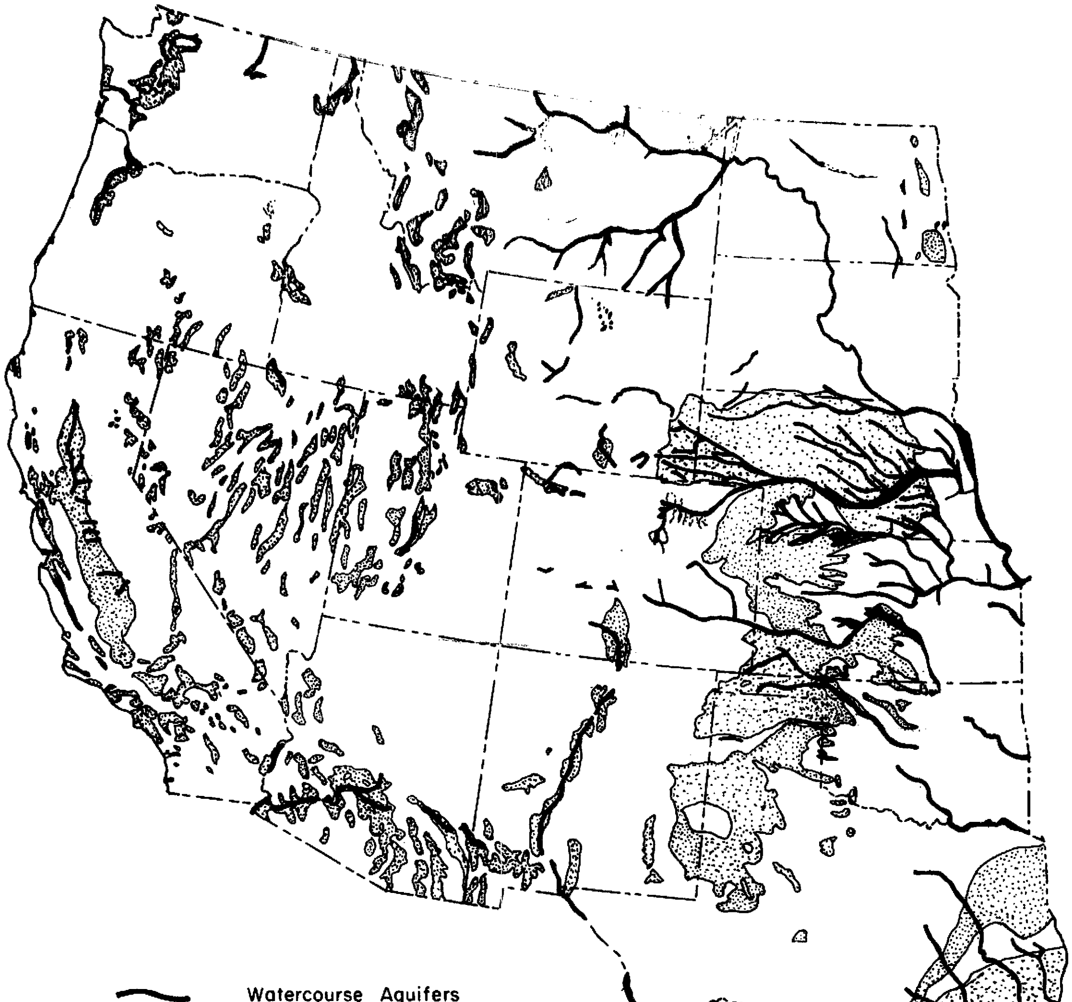

Fig. 1. Watercourse and other unconsolidated aquifers in the conterminous 17 Western States (after Thomas, 1951).

of the District Offices of the U.S. Geological Survey in the 17 Western States. Information requested of these offices included:

1. An indication of the major river reaches in each state in which there exists an alluvial aquifer of economic consequence hydraulically connected to a perennial stream.
2. References to published reports and reports in progress which describe the pertinent geohydrological components of each system.
3. Comments on the principal water management problems, causes, and needs within each of the major stream-aquifer systems.

Personnel of the U.S. Geological Survey showed much interest in this study and responded with considerable information. A tabulation of the results received is given in Appendix A. The following sections summarize the information and supplement it with pertinent geohydrological information drawn from the U. S. Geological Survey Water-Supply Papers and State Water Agency publications listed in Appendix A. For convenience, the stream-aquifer systems are classified below by river basins rather than by states.

Columbia and Snake River Basins

The dominant aquifers of the Columbia and Snake River Basin are the extrusive volcanic rocks of the large Columbia Lava Plateau. Several thousands of feet of lava provide large storage capacities, and large openings allow rapid intake and movement of water. The Columbia, Snake and other tributaries deeply dissect the lava beds. Alluvium along the rivers is hydraulically connected with the lava beds, but the importance of the alluvium as a water supply is minor compared to the lava.

Parts of the Spokane and Yakima River valleys, tributaries of the Upper Columbia River, were listed by USGS personnel as major stream-aquifer systems. The Walla Walla, in both Washington and Oregon, and part of the Willamette Valley in Oregon also comprise major stream-aquifer systems. Two reaches of the Snake and six of its tributaries (Raft, Big Lost, Little Lost, Big Wood, Boise, and Payette Rivers) were identified as major systems in Idaho. Three Snake River tributaries in Oregon (Malheur, Powder, and Grande Ronde) were so identified.

The Great Basin

The valleys of the Great Basin occupy structural and topographic lows and are bordered by mountain and plateau areas of Nevada, Utah and California. The fill of each valley consists of coalescing alluvial fans deposited at the mouths of canyons. During the Pleistocene, precipitation was high and slopes were steep, resulting in coarse materials being deposited in the lower portions of the fills. During the Recent epoch the climate became arid, flows diminished, and finer debris contributed to the valley fills. The interbedded aquifers and aquicludes, along with bowl-shaped structure, resulted generally in artesian conditions.

Present-day streams emerging from the mountains flow onto the valley floors and end in lakes and sinks. A number have significant alluvial aquifers, most of which are hydraulically connected with the deeper artesian aquifers.

Major stream-aquifer systems in Nevada include reaches of the Humboldt, Truckee, and Walker Rivers. Those in Utah, all in the Great Salt Lake Basin, include portions of the Jordon, Provo, Sevier, Beaver, Weber, Ogden, and Bear Rivers.

Colorado River Basin

The Upper Colorado River Basin is composed of extensive areas of sedimentary strata, principally sandstones and limestones, having poor hydraulic characteristics and low natural recharge. Some alluvial deposits exist, but the Green River in Wyoming was the only one considered as a major stream-aquifer system.

The Salt and Gila Rivers, tributaries to the lower end of the Colorado River, have large, highly developed aquifers. Reaches of these rivers are listed as stream-aquifer systems but due to reservoirs, diversions, groundwater use, and phreatophytes, flow is no longer perennial. A large storage capacity is available, however, and these rivers may become important again as stream-aquifer systems when additional surface water is imported into Central Arizona.

Portions of the main stem of the lower Colorado River contain alluvial aquifers of importance and represent systems worthy of consideration for integrated management operations.

Western Gulf of Mexico Basins

The Rio Grande heads in the mountains of southwestern Colorado, flows through a large structural basin of deep fill (San Luis Valley), then southward into New Mexico and Texas. The recent alluvium along the river in Colorado is hydraulically connected with deeper artesian aquifers as well as an extensive shallow unconfined aquifer, resulting in an extremely complex system.

Conditions in the lower Rio Grande are somewhat similar to that of the Salt and Gila Rivers of Arizona. Several reaches of the main stem would be considered as stream-aquifer systems, as well as part of the Pecos River in Texas.

Other major stream-aquifer systems in Texas include reaches of the Colorado River and its tributary, Beale Creek; part of the Guadalupe River and its tributary, the San Marcos River; and the Brazos, San Jacinto, and Nueces Rivers. All of these rivers flow across the Gulf Coastal Plain in their lower reaches, and are in hydraulic connection in various degrees with lower artesian interbedded aquifers.

Missouri River Basin

A large portion of the Missouri River Basin is composed of plains and plateaus underlaid with sedimentary rocks of the Paleozoic, Mesozoic and Middle Tertiary. The upper part of the basin was glaciated and carries a mantle of glacial drift. The drift contains scattered aquifer material and also serves as a source of recharge to the bedrock aquifers below. However, watercourse aquifers provide the largest production of the area.

The main stem of the Missouri contains important stream-aquifer systems, although on-stream surface reservoirs have inundated many of the aquifers in the Dakotas. Reaches of the Yellowstone River in North Dakota are also major stream-aquifer systems. The Bighorn, Wind and North Platte River Valleys of Wyoming contain major systems. In South Dakota the Grand, Cheyenne, Bad, White, James, Vermillion, and Big Sioux Rivers are considered such. The Platte River, including the North Platte of Wyoming and Nebraska; the South Platte of Colorado and Nebraska; and the main stem in Nebraska have important stream-aquifer connections. Also, the Republican, Smoky Hill, and Solomon Rivers of Nebraska and Kansas are major stream-aquifer systems. Although the upper Missouri and its tributaries have watercourse aquifers with little or no connection with other aquifers, the Platte, Republican, Smoky Hill, and Solomon Rivers cross the Ogallala formation of the

High Plains in Nebraska and Kansas. These streams are in hydraulic connection with the groundwater in the Ogallala formation.

Lower Mississippi River Basin

Tributaries of the lower Mississippi identified as major stream-aquifer systems include portions of the Arkansas River in Colorado and Kansas, and its tributaries the Cimarron and North Canadian Rivers. Also, the Red and Washita Rivers in Oklahoma are listed. These rivers traverse areas where aquifers other than the Recent Alluvium are relatively unimportant, as well as areas having other important aquifers in hydraulic connection.

Typical Water-Management Problems

Identification of many water-management problems, causes, and needs within 89 stream-aquifer systems in the Western United States was provided by State Conservation Engineers of the Soil Conservation Service, United States Department of Agriculture. A summary of the results obtained on questionnaires, using the major stream-aquifer systems identified by USGS personnel, is given in Table 1.

Of the 89 stream-aquifer systems reported on by the SCS personnel, 64 percent have drainage problems and nearly 54 percent have nonbeneficial uses of water related to an excessively high water table. Causes of these conditions include canal seepage, reservoir seepage, excessive irrigation, water use on adjoining uplands, and leakage from artesian zones.

Quality problems were reported for 67.5 percent of the stream-aquifer systems. Although not an objective of this treatise, this high percentage points up the need to always consider the quality aspects when planning water-management programs.

Table 1. Water-management problems, causes, and needs in major stream-aquifer systems.[a]

		Percent of the 89 reported		
Problems		Minor	Major	Total
1.	Drainage	25.9	38.1	64.0
2.	Nonbeneficial uses	33.6	20.3	53.9
3.	Surface water-groundwater conflict or interference			
	a. now a problem	10.1	11.2	21.3
	b. potentially a problem	13.5	19.1	32.6
4.	Quality problems			
	a. chemical	20.3	19.1	39.4
	b. bacteriological	5.6	6.7	12.3
	c. physical	12.4	3.4	15.8
5.	Other	2.2	7.9	10.1
Causes				
1.	Canal seepage	29.2	20.3	49.5
2.	Reservoir seepage	7.9	4.5	12.4
3.	Excessive irrigation	20.3	36.0	56.3
4.	Water use on adjoining uplands	18.0	15.7	33.7
5.	Leakage from artesian zones	6.7	3.4	10.1
6.	Poor natural drainage	34.9	19.1	54.0
7.	Lack of coordinated use of groundwater and surface water	30.4	16.8	47.2
8.	Other	2.2	9.0	11.2
Needs				
1.	Artificial drainage	27.0	31.5	58.5
2.	Phreatophyte control	24.7	11.2	35.9
3.	Improvement of irrigation	14.6	43.9	58.5
4.	Sealing of canals and/or reservoirs	20.3	25.9	46.2
5.	Planned integrated management of groundwater and surface water	25.9	21.4	47.3
6.	More information on system responses to changes in management practices	24.7	20.3	45.0
7.	Legislation allowing integrated management of groundwater and surface water	15.7	9.0	24.7
8.	Other	3.4	9.0	12.4

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[a] Summarized from questionnaire returned by State Conservation Engineers, SCS, USDA. Detailed returns are tabulated in Appendix B.

The problem of conflicts between surface water and groundwater users, such as infringement of surface-water rights caused by use of groundwater, exists in over 21 percent of the stream-aquifer systems. It is expected to become a problem in another 33 percent as groundwater users increase. In this regard, SCS personnel reported that planned coordinated or integrated management of interrelated groundwater and surface water is needed in over 47 percent of the stream-aquifer systems. They also indicated that information is needed on system responses to changes in water management practices in 45 percent of the systems.

DESCRIPTIONS OF STREAM-AQUIFER SYSTEMS

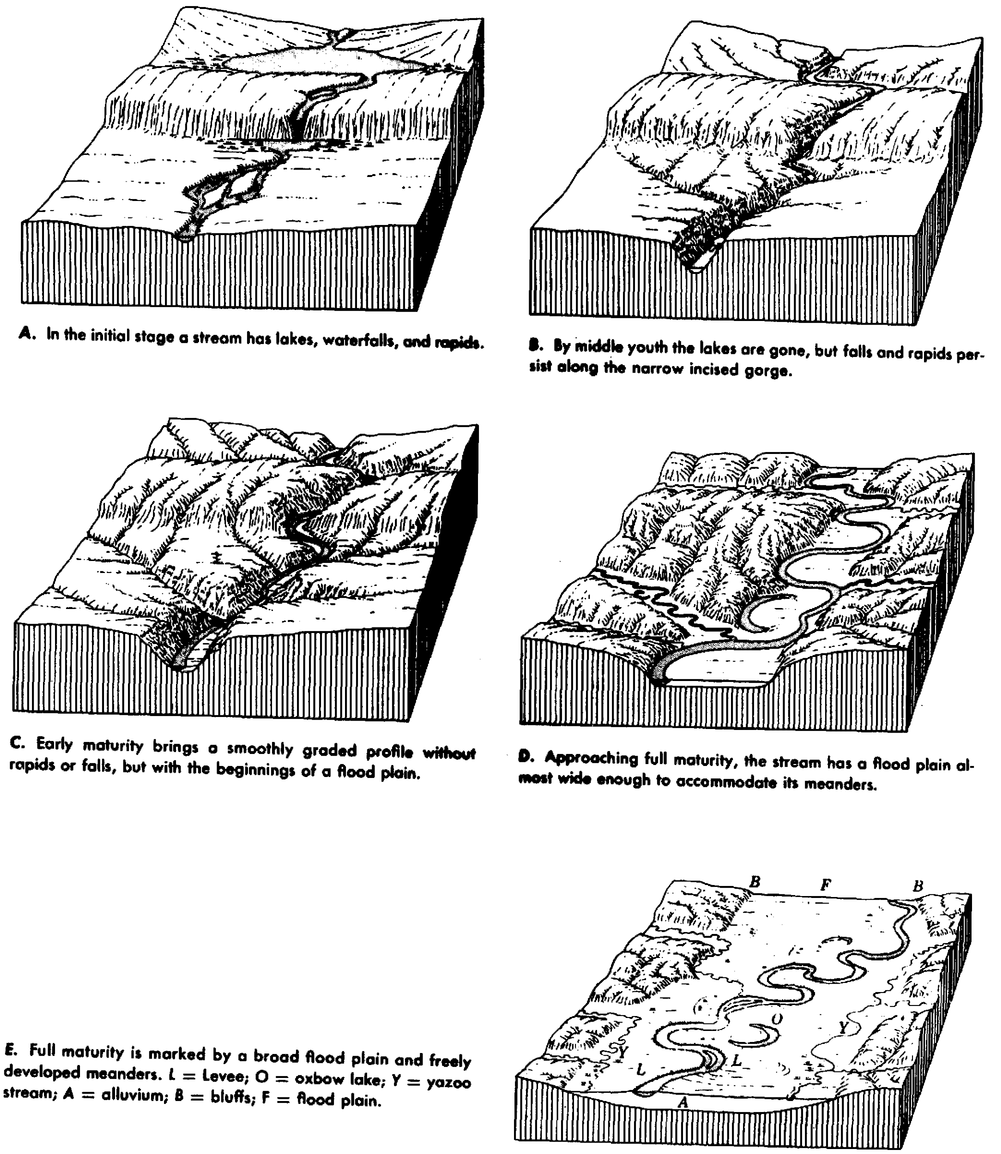
Qualitative Classifications

The geologic processes of river downcutting, lateral erosion, and deposition which have produced the present day valleys and alluvial aquifers are described qualitatively in the literature of geomorphology and physical geography such as Thornbury (1954) and Strahler (1960). Rivers and valleys are commonly classified as young, mature, and old. As shown in Figure 2, the latter stage of development of valleys is characterized by a wide flood plain constructed by lateral erosion, an alluvial deposition,and a meandering stream.

Other qualitative classifications of valleys include: (1) classification according to genesis (consequent, subsequent, insequent, obsequent, and resequent); (2) classification according to controlling geologic structure (homoclinal, anticlinal, synclinal, fault, fault-line, and joint); and (3) classification according to effects of change in base level (drowned, rejuvenated).

Fisk (1944, 1947) classified alluvial deposits along the lower Mississippi River as graveliferous and non-graveliferous. In examining logs of several thousand wells, he found that the graveliferous deposits generally form the basal portion of the alluvial fill. The coarsest materials are commonly found at the mouths of tributary valleys in a series of alluvial fans. Within the non-graveliferous classification, Fisk made the following subdivisions:

1. Meander deposits
    a. Point-bar deposits
    b. Abandoned channel fillings
    c. Natural levee deposits
2. Backswamp deposits
3. Braided stream deposits
4. Deltaic plain deposits



A. In the initial stage a stream has lakes, waterfalls, and rapids.

B. By middle youth the lakes are gone, but falls and rapids persist along the narrow incised gorge.

C. Early maturity brings a smoothly graded profile without rapids or falls, but with the beginnings of a flood plain.

D. Approaching full maturity, the stream has a flood plain almost wide enough to accommodate its meanders.

E. Full maturity is marked by a broad flood plain and freely developed meanders. *L* = Levee; *O* = oxbow lake; *Y* = yazoo stream; *A* = alluvium; *B* = bluffs; *F* = flood plain.

Fig. 2. Stages of river and valley development (after Strahler, 1960).

The above classifications are illustrated in the generalized cross section shown in Figure 3, taken from Davis and DeWeist (1966). Davis and DeWeist also observe that most alluvial valley deposits have a simple vertical succession from coarse sands or gravels near the bottom of the channels to silt and clays at the top. They indicate that, in general, alluvial deposits of modern or Late Pleistocene rivers are from 20 to 150 feet thick and have at least five, and, more commonly, several tens of feet of coarse sands and gravels near their bases.

Leopold and others (1954, 1964) have presented classification schemes of alluvial valleys based upon the succession of fills and the number of terraces remaining. The basic classification of "inset" and "overlapping" alluvial fills and the further classifications by number of fills and number of terraces is shown in Figure 4. Leopold and Maddock (1953), Leopold and Wolman (1957) and Schumm (1963a, 1963b) have studied the geometry of river meanders in alluvial valleys.

The term "sinuosity" has been utilized by fluvial geomorphologists and river mechanists and is defined as the ratio of channel length to the down-valley distance. If this index, the sinuosity, is greater than 1.5 the river is considered meandering and if the index is less than 1.5 it is considered straight.

By studying field situations, empirical relationships have been derived between stream discharge, channel width and depth, meander length, and sediment size. Correlations relating meander amplitude to channel width have been attempted but have generally shown poor relationships. The amplitude of the meanders is determined more by erosion characteristics of the stream banks and by other local factors than by any hydrodynamic principle. A relation which holds for a predominance of cases is the ratio of the mean curvature radius of the meanders to the width of the stream.

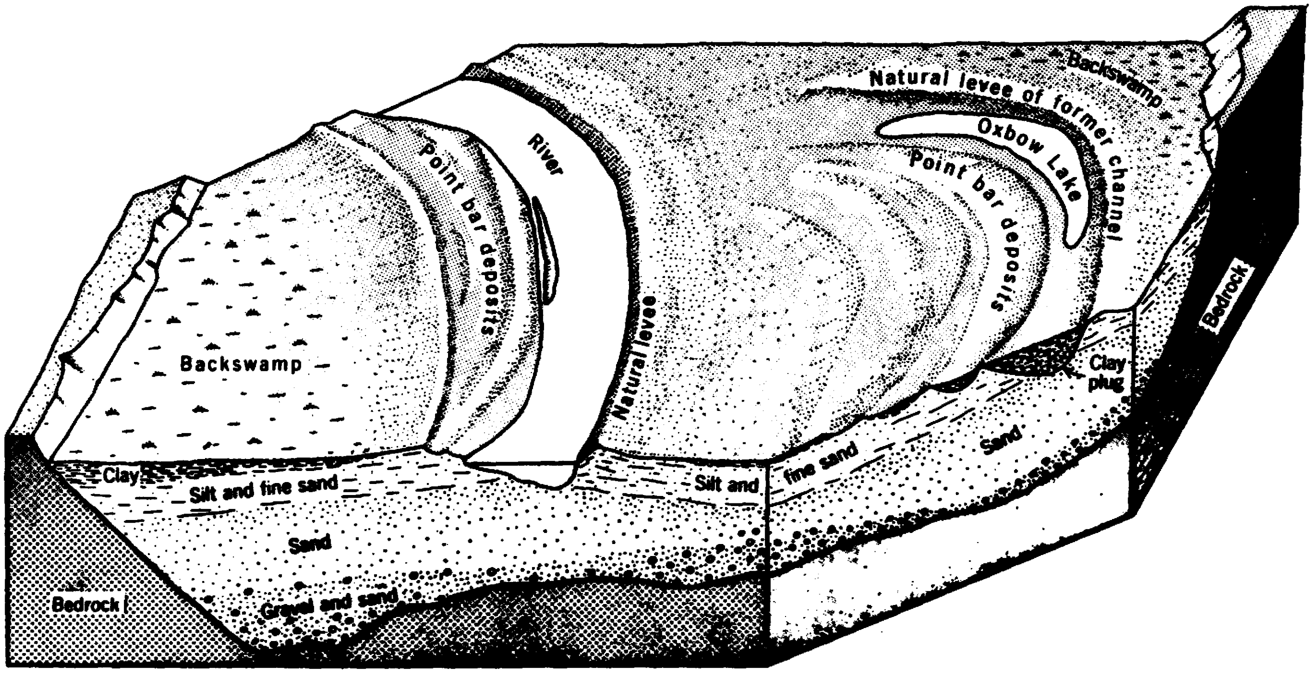


Fig. 3. Typical river-valley alluvial deposits (after Davis and DeWiest, 1966).

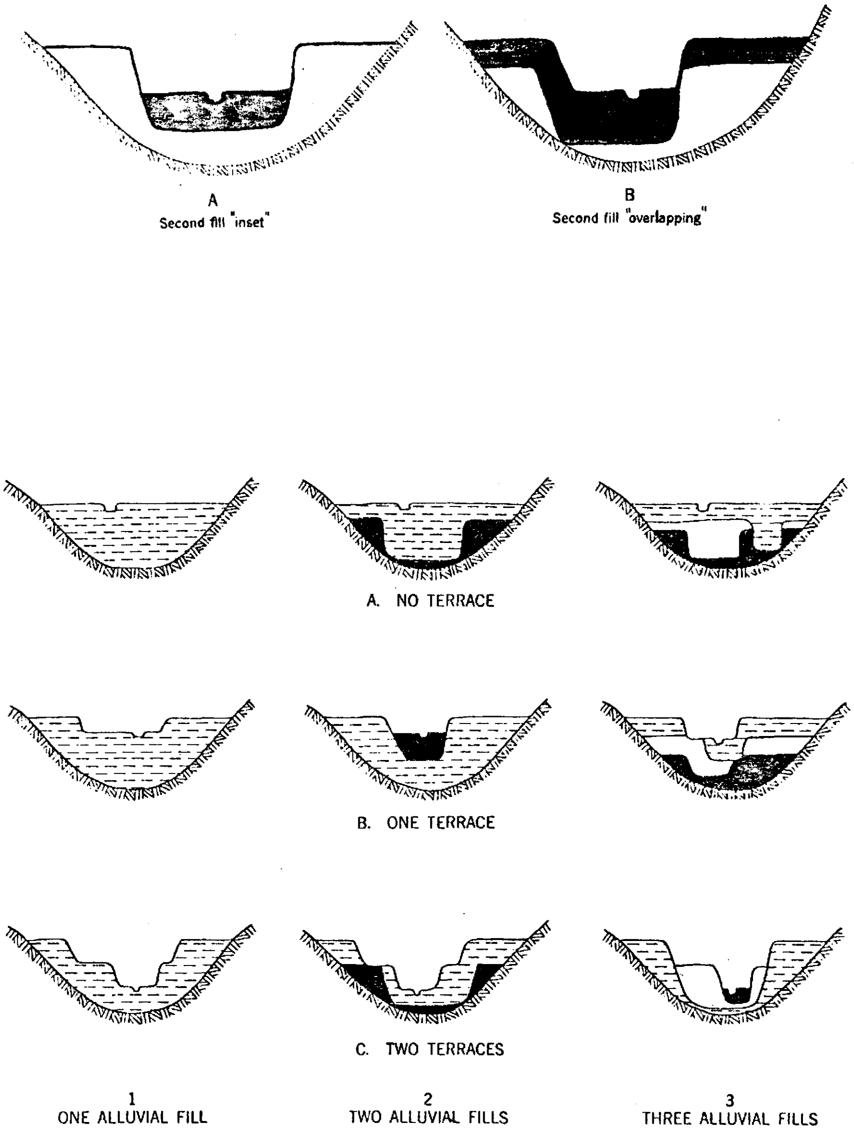


Fig. 4. Classification of river-valley alluvial fills (after Leopold and others, 1954, 1964).

This ratio generally lies between two and three. Leopold, Wolman and Miller (1964) stated that "when a map of the reach of the Mississippi River is laid next to one for a small creek, each to a scale that makes the meander length equal on the printed page, one cannot tell by inspection which is a map of a large river and which of a small river." These researchers also found that the wavelength of a valley meander is generally about ten times the wavelength of the river meanders within the valley.

The foregoing discussion points up the fact that the geologic history of a river valley may be reconstructed by means of a systematic detailed study of the topographic forms and alluvial deposits within the valley. Unfortunately, the reverse is rarely possible; i.e., knowing something of the climatic conditions, gradient changes, and sediment sources over geologic history it is not possible to predict the log of a well at a particular location except in very general terms.

Quantitative Description of Stream-Aquifer Systems

In order to simulate a complex stream-aquifer system adequately, the interrelationships and interactions of the pertinent components of the system must be identified and quantified. In general, a system can be divided into three parts: (1) input of material and/or energy into the system, (2) interaction of the pertinent components within the system, and (3) an output or response of the system. An understanding of the relationships of these parts and their interacting elements is basic to the "systems" concept.

Figure 5 shows a general scheme of a stream-aquifer system including the usual pertinent elements contributing to input, the system parameters, and the response variables. All but a few of these elements must be described in terms of time as well as space coordinates. Thus, if quantities and rates are inserted in Figure 5 they can only represent one point in time and space, and must of necessity be related to the state of those variables during the immediately preceding time periods as well as to the immediately surrounding points in space.

Input variables

Input variables are considered to be positive if they add water to the system and negative if water is withdrawn from the system. All of the input variables are functions of both the space and time coordinates.

Precipitation input. The portion of precipitation which contributes directly to the system may include the contribution from precipitation falling on the soil directly above the aquifer as well as overland flow and runoff from higher elevations tributary to the stream valley. These variables are stochastic in both time and space but are often modified by the activities of man. For instance, cultivation and cropping influence interception, evapotranspiration, and infiltration characteristics so that a different proportion of the precipitation reaches the groundwater system. Other activities of man which may modify the precipitation input include (1) the diversion and use of a portion of the precipitation falling on tributary lands, (2) activities which change the normal groundwater levels thereby influencing the amount and location of water rejected, added, or discharged, and (3) weather modification, either intentional or unintentional.

Input from irrigation activities. In many of the irrigated valleys of the western United States the input to the stream-aquifer system from irrigation activities is of greater magnitude than that from precipitation. In most cases, however, the variability in both time and space may be as great as found in an area in which precipitation is the predominating variable. It tends, however, to be more of a deterministic than stochastic nature. This is because of both the nature of the supply and the location of the points of irrigation water losses. In general, although irrigation water supplies may vary from year to year, the variability will be smaller than natural precipitation if storage facilities are available. An areal variability may occur because (1) only part of the land is irrigated, (2) of a wide difference in irrigation application efficiencies by various farm operators, and (3) of losses of intense proportions at certain locations such as under canals and reservoirs. Thus the time-pattern of irrigation losses to the groundwater system at any one location may be similar from year to year but the variability may be quite large from point to point within a system.

Evapotranspiration factor. Direct evaporation from the groundwater system may occur at points where the water table is close to the land surface. Also, under certain conditions of high water table and vegetation, transpiration losses may occur directly from the water table. Phreatophytes, such as salt cedars, cottonwoods, and willows, have the ability to extract water directly from the groundwater system. This loss to the system may occur under natural conditions and may be either increased or decreased by man's activities depending upon how they influence the height of the water table and the growth of vegetation. For any set of physical conditions, the amount and timing of evapotranspiration losses directly from the groundwater system are fairly consistent and reasonably predictable. Pertinent climatic factors are the air temperature, humidity, wind activity, and solar radiation. Although these climatic factors vary, the range of variance is commonly not as great as is found in the precipitation or irrigation input variables discussed above. Characteristically, the evapotranspiration has an annual cycle, but may also have a long-term trend due to gradual changes in water table levels or vegetation.

Withdrawals from wells. Water pumped from wells for irrigation, municipal, or industrial purposes is distinctly a man-made, negative, input factor. The amount and timing of this factor is somewhat probabilistic in that the uses to which the water is put may be dependent upon climatic or other random variables. Figure 5 shows a portion of the water pumped returning to the groundwater system as one of the input components. The amount and timing of this return-flow component is dependent upon many of the same factors as discussed under precipitation and irrigation losses above.

Other hydraulically-connected aquifers. In those stream-aquifer systems other than the most simple (watercourses with alluvial deposits in impermeable bedrock channels) flow into or out of the recent alluvium will occur wherever it is in contact with other aquifers. The direction of flow will be dependent upon the relative piezometric heads in the adjoining aquifers. The flow may be reversed, increased, or decreased due to man's activities influencing one or more of the aquifers concerned. This factor may be of considerable importance in many instances, but is often neglected because of unknown relationships between the aquifers.

Artificial recharge. Artificial recharge of the groundwater reservoir may be an important part of the integrated management of the groundwater and surface-water resources of a stream-aquifer system. Artificial recharge, as opposed to recharge incidental to irrigation activities, is planned replenishment of water to the groundwater system. Many studies have been made and techniques developed for effective artificial recharge. For the purposes of this treatise the input to the groundwater system by artificial recharge is considered as only that part which actually reaches the groundwater table.

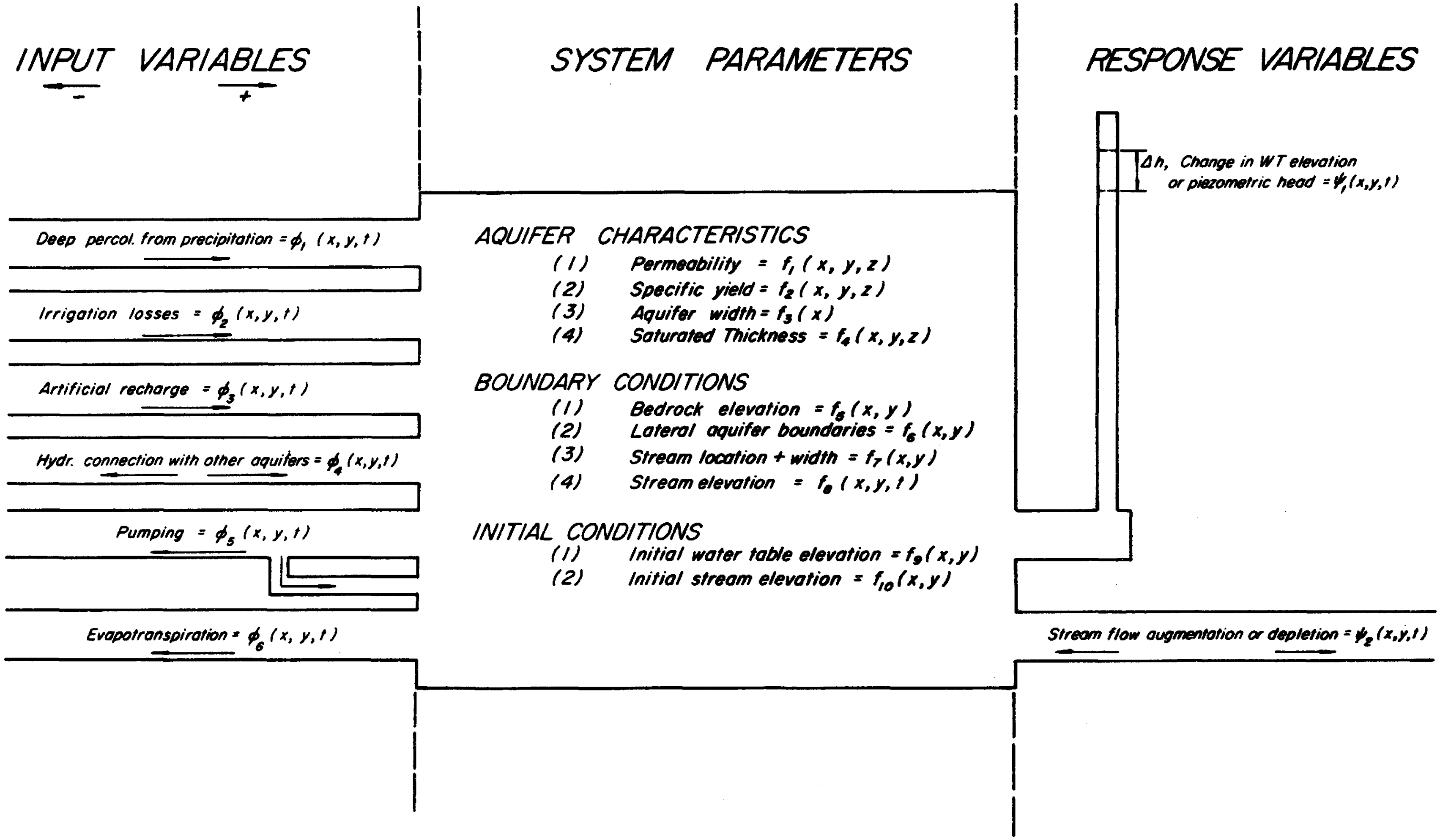


Fig. 5. Principal components of stream-aquifer systems.

System parameters

The system which transforms the input variables into response variables contains many interacting elements. The fate of these elements in time and space must be quantitatively described. They may be conveniently divided into three categories: (1) aquifer characteristics, (2) boundary conditions, and (3) initial conditions.

Aquifer characteristics. Two hydraulic and two geometric characteristics of the aquifer are pertinent. The hydraulic characteristics, permeability and specific yield, are functions of space but not time. Various field and laboratory measurements are available for estimating the permeability and specific yield within an aquifer. U.S. Geologic Survey publications show a wide range of values for permeabilities of Recent alluvium along streams. In general, however, the value of permeability lies in the neighborhood of 1000 to 5000 gallons per day per square foot for good alluvial aquifers. Values of over 10,000 are sometimes encountered as well as values below 1000. The range of values for specific yield of alluvial aquifers is not as great, generally ranging between 0.15 and 0.25.

The geometric characteristics of an aquifer of importance are the width and the saturated thickness. The width of an aquifer may vary slightly as the water table fluctuates up or down, but it is usually a minor factor compared to the total width and therefore neglected. The aquifer width may vary with length along the river valley. The saturated thickness varies in both time and space. At any location, the product of the saturated thickness and the permeability is called the transmissibility of the aquifer at that point. The transmissibility is an index of the water carrying capacity of the aquifer. If the fluctuation in saturated thickness is small compared to the total saturated thickness, the thickness or transmissibility may be considered constant in time with little error. However, for the thin aquifers often encountered in alluvial systems this idealization may bring erroneous results.

Boundary conditions. Impermeable, semipermeable, and hydraulic boundaries exert important influences on the behavior and response of stream-aquifer systems. These boundaries may include: (1) the elevation of the bedrock underlying the alluvium; (2) the location and shape of the lateral boundaries along the aquifer sides; (3) the location, width and course of the stream; and (4) the fluctuation of the stream surface. If the aquifer is of the watercourse type embedded in an impermeable channel within the bedrock, the first two items listed will constitute impermeable boundaries. If the alluvial material is in hydraulic contact with older aquifers, either or both the bedrock or lateral boundaries may be semipermeable. The portions of such boundaries which are semipermeable, allowing interchange of water between aquifers, must be located and evaluated in order to adequately simulate the system. The hydraulic boundary of concern in the stream-aquifer system is the stream. Interchange of water from the aquifer to the stream is influenced by the relative positions of the water table within the aquifer and the water level in the stream. Thus a fluctuation of the stream level caused by an outside source will influence the response of the system as measured by the interchange of water between the aquifer and the stream.

Initial conditions. The state of two time-dependent aquifer parameters influence the response of the system and must be defined at time zero prior to beginning a simulation. These parameters are the initial water table elevations within the aquifer and the initial stream-surface elevation. These initial conditions are not necessarily constant in space. For instance, the initial water table elevation may vary in directions at right angles to the stream as well as parallel to the stream.

Output, or system response

Two measurements of system response are of interest here. One is the change of water table elevations in both time and space, and the other is the amount of groundwater--surface water interchange with time and distance along the stream. The changes in water table elevations are a reflection of the change in storage of water within the system. The interchange of water between the aquifer and the stream is an exterior representation of the behavior of the system in response to various input conditions and system states.

SIMULATION TECHNIQUES

Many simulation techniques have been developed and are suitable for simulating stream-aquifer systems. Desirable attributes of techniques for modeling such systems have been suggested by the author and his colleagues (Bittinger, Duke, and Longenbaugh, 1967). These attributes are:

1. Ability to simulate nonsteady conditions.
2. Ability to simulate at least two space dimensions.
3. Ability to simulate irregular geometric and hydraulic properties realistically without undue idealization.
4. Ability to simulate nonlinear conditions.
5. Ability to simulate, in both time and space, the simultaneous effects of many inputs and interacting elements of the system.
6. Capable of being easily modified to facilitate verification and to study effects of many different operating conditions.
7. Capable of being readily adapted to different study areas by introducing new geologic and hydrologic data.
8. Provide results in immediately usable forms (tables, graphs, etc.).
9. Utilize equipment and personnel readily available.
10. Provide rapid analyses at reasonable costs.

Physical Models

Models of groundwater systems which faithfully represent the geometry of the systems have historically been accomplished with sand tanks. A basic problem with sand-tank models is the disproportionately large capillary zone in the model compared to the prototype. This disadvantage can be overcome, but for a complex nonsteady state situation a sand-tank model requires either a great amount of labor for its operation or extremely complicated and expensive instrumentation. One can see that attempting to (1) simulate several hundred wells on various pumping schedules, (2) provide for deep percolation and aquifer interchange at various locations and time distributions, and (3) measure the water-table response and streamflow accretion with time at many points would require very sophisticated instrumentation. In addition, modeling of varied permeability distributions is difficult and changing the same is a major job.

Of the physical models available for simulating stream-aquifer systems, the electric analog is the most versatile. Two types of electric analogs are in use. One, the active-element analog, consists of electrical circuitry capable of solving the differential equations of groundwater flow. Construction of an active-element electric analog of a size necessary to simulate the many interacting factors of inflow, system parameters and response for a complex stream-aquifer system is expensive and requires the services of expert electronic technicians for its construction and operation. An advantage of the active-element analog is its adaptability to different problems and different areas.

The passive-element electric analog (resistance-capacitance network) is utilized for studying unsteady state groundwater systems. The technique has been utilized by the petroleum industry and in recent years by the U. S. Geological Survey in groundwater studies. Electrical resistors and capacitors are chosen in particular sizes to simulate permeabilities and storage coefficients within an aquifer. Thus, the analog is specifically built for a particular area and is not easily adapted to a new area. Generally a completely new model is built for each area studied.

Mathematical Models

If mathematical expressions describing the interrelations of the input variables and the system parameters and their influence upon the response variables can be stated, a mathematical model may be constructed. Mathematical models may be wholly deterministic or part deterministic and part probabilistic. A general nonlinear partial differential equation may be derived from Darcy's law and continuity considerations which describes three-dimensional flow in an unconfined aquifer:

$$\frac{\partial}{\partial x}(K_x h \frac{\partial H}{\partial x}) + \frac{\partial}{\partial y}(K_y h \frac{\partial H}{\partial y}) + \frac{\partial}{\partial z}(K_z h \frac{\partial H}{\partial z}) = S \frac{\partial H}{\partial t} + \frac{Q}{\delta x \delta y \delta z} \quad . \; . \quad (1)$$

where K equals the permeability in the x, y, and z directions at any point (x,y,z), h equals saturated thickness of the aquifer, H equals the hydraulic head, or potential, above an established datum, S equals storage coefficient or specific yield of the aquifer at point (x,y,z), Q equals net inflow, and t equals time.

Exact solutions

Two methods of obtaining an approximate solution of this differential equation are common. If flow is predominately horizontal the flow in the vertical direction may be neglected. In addition, if the total saturated thickness h is large compared to its change with time, h may be considered constant. If, in addition, $K_x = K_y = K_z$(i.e., isotropic conditions) the following equation is evolved:

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = \frac{S}{Kh}\frac{\partial H}{\partial t} + \frac{Q}{\delta x \delta y \; Kh} \quad . \; . \; . \; . \; . \; . \; . \; . \; (2)$$

Equation 2 is a linear partial differential equation in two dimensions which has many particular solutions for various boundary and initial conditions. The equation is commonly referred to as the heat conduction equation, or the diffusion equation. Exact analytic solutions of

Equation 2 for various groundwater situations may be found in Glover (1964) and Hantush (1964). These and other solutions are summarized in Maasland and Bittinger (1963). If the idealizations necessary to make the mathematics tractable are not too excessive compared to actual field conditions, excellent results may be obtained from the analytic solutions. The aquifer must be modeled assuming simple geometric shapes and the aquifer characteristics must be considered constant throughout the system. The influence of hydraulic and impermeable boundaries must be taken into consideration by utilizing the "image theory." The theory of superposition is utilized to sum up the effects of several wells, boundaries and other effects on the water table at a point. This will result in error if in fact the prototype system is not truly linear, as is the situation when fluctuations of the water table are large compared to the total saturated thickness of the aquifer.

Finite-difference approximations

For two-dimensional flow in an unconfined aquifer Equation 1 may be rewritten as follows:

$$\frac{\partial}{\partial x}\left(Kh \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(Kh \frac{\partial H}{\partial y}\right) = S \frac{\partial H}{\partial t} + \frac{Q}{(\delta x)(\delta y)} \quad . \; . \; . \; . \; . \quad (3)$$

This is a nonlinear partial differential equation which more accurately describes the groundwater flow in space and time within thin unconfined aquifers than does the linearized version (Eq. 2). Since no analytical solution exists for this nonlinear equation, it must be solved by numerical methods. Numerical methods have long been available, but have not come into their own until large and rapid digital computers have allowed economical solution of large sets of such equations. Many recent texts such as Richtmyer (1957) and Varga (1962) discuss numerical methods for solution of partial differential equations.

The bases of numerical methods for solving Equation 3 require that it be stated in finite-difference form. When a function f and its derivatives are single-valued, finite, and continuous functions of x, Taylor's expansion gives:

$$f(x+\Delta x) = f(x) + \Delta x f'(x) + \frac{1}{2}(\Delta x)^2 f''(x) + \frac{1}{6}(\Delta x)^3 f'''(x) + \;.\;.(4)$$

and

$$f(x-\Delta x) = f(x) - \Delta x f'(x) + \frac{1}{2}(\Delta x)^2 f''(x) - \frac{1}{6}(\Delta x)^3 f'''(x) + \;.\;.(5)$$

Addition of these expansions results in:

$$f(x+\Delta x) + f(x-\Delta x) = 2f(x) + (\Delta x)^2 f''(x) + 0(\Delta x^4)\;.\;.\;.(6)$$

where $0(\Delta x^4)$ denotes the remaining terms containing fourth and higher powers of Δx in the series expansion. If one assumes that such terms are negligible in comparison with the lower powers of Δx it follows that:

$$f''(x) = \frac{d^2 f(x)}{dx^2} = \frac{f(x+\Delta x) - 2f(x) + f(x-\Delta x)}{(\Delta x)^2}\;.\;.\;.\;.\;.(7)$$

with a leading error on the right-hand side of order $(\Delta x)^2$.

In the same manner, subtraction of Equations 4 and 5 and neglect of terms of order of $(\Delta x)^3$ and above leads to:

$$f'(x) = \frac{df(x)}{dx} = \frac{f(x+\Delta x) - f(x-\Delta x)}{2(\Delta x)}\;.\;.\;.\;.\;.\;.\;(8)$$

with an error of order $(\Delta x)^2$.

Equation 8 is an approximation of the slope of the tangent at P as indicated by the chord AB in Figure 6. This is commonly referred to as the central-difference approximation of the first derivative or slope. The slope of the tangent at P may also be approximated by the slope of the chord PB, giving the forward-difference formula

$$f'(x) = \frac{f(x+\Delta x) - f(x)}{\Delta x}\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;.\;(9)$$

or the slope of the chord AP, giving the backward-difference formula:

$$f'(x) = \frac{f(x) - f(x-\Delta x)}{\Delta x} \quad \ldots\ldots\ldots\ldots (10)$$

Both the forward-difference and the backward-difference formulas may be derived directly from Equations 4 and 5 by assuming the second and higher powers of Δx to be negligible. Therefore, the leading errors for the forward and backward-difference formulae are both of order Δx.

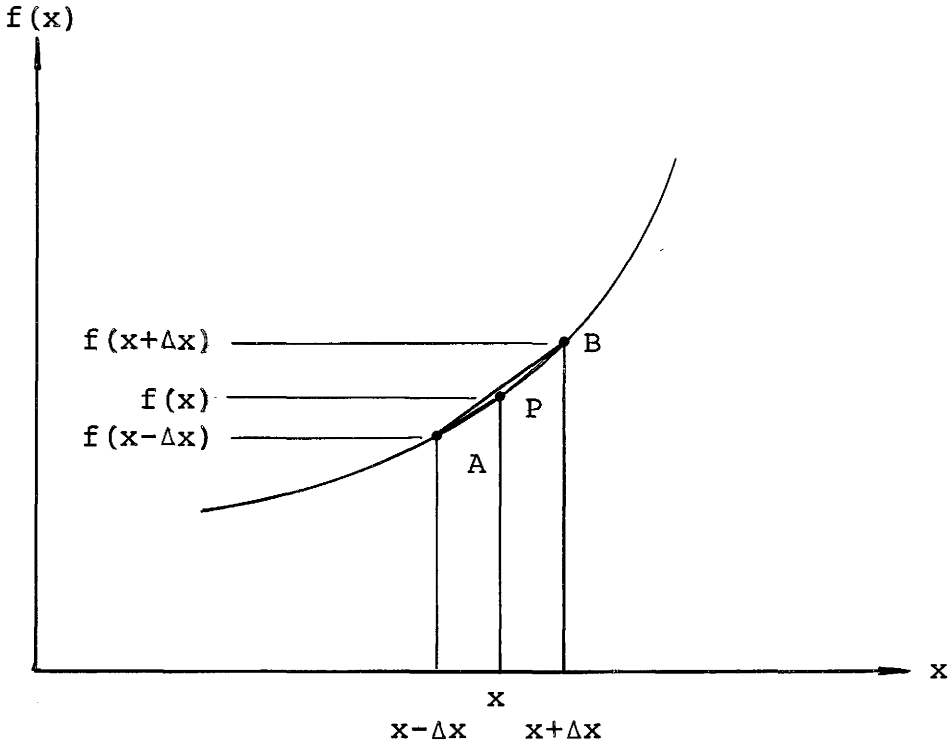


Fig. 6. Graphical representation of finite-difference schemes for slope at P.

When more than one independent variable is involved, it is convenient to use a subscript notation. Assume, as in Equation 2, that H is a function of the three independent variables x, y, and t. The x-y plane is then subdivided into rectangular grids of dimension x and y. Layers of x-y planes are spaced at intervals of time t. Therefore, the coordinates (x,y,t) of any grid intersection may be defined by $\Delta x = i\Delta x, \Delta y = j\Delta y$, and $t = n\Delta t$; where i, j, and n are positive integers. The value of H at each grid point may then be denoted by $H(i\Delta x, j\Delta y, n\Delta t) = H_{i,j,n}$. Using this notation, Equation 2 may be written in one finite-difference form as:

$$\left(\frac{H_{i-1,j,n}-2H_{i,j,n}+H_{i+1,j,n}}{(\Delta x)^2}\right) + \left(\frac{H_{i,j-1\overset{n}{/}}-2H_{i,j,n}+H_{i,j+1,n}}{(\Delta y)^2}\right)$$

$$= \frac{S}{Kh}\left\{\left(\frac{H_{i,j,n+1}-H_{i,j,n}}{\Delta t}\right) + \frac{Q}{S\Delta x\Delta y}\right\} \quad . . . (11)$$

Equation 11 is an explicit finite-difference representation of Equation 2, in that only one term, $H_{i,j,n+1}$, is unknown if calculations are started with known values of H at all x and y at an initial time t_o.

Development of a Mathematical Model for Stream-Aquifer Systems

The nonlinear equation given in Equation 3, applicable to nonhomogeneous unconfined aquifers, may be approximated by the following finite-difference equation:

$$\left(\frac{KhH_{i-1,j,n}-2KhH_{i,j,n}+KhH_{i+1,j,n}}{(\Delta x)^2}\right) +$$

$$\left(\frac{KhH_{i,j-1,n}-2KhH_{i,j,n}+KhH_{i,j+1,n}}{(\Delta y)^2}\right) = S\left(\frac{H_{i,j,n+1}-H_{i,j,n}}{\Delta t}\right) + \frac{Q}{\Delta x\Delta y}$$

$$. . . . . (12)$$

The nonlinearity of this equation (i.e., variable coefficients, Kh) may be handled by adjusting the value of h for each grid point after each time-step calculation and by considering K to be uniform throughout each grid cell. If h does not change greatly during a time step, and if K changes gradually in respect to the x and y distances, the error involved in making these assumptions should be small.

Equation 12, like Equation 11, is an explicit finite-difference representation which can be solved directly for the value of H at any point (x,y) for the next point in time. As is proven in most numerical analysis texts, this form is not stable (i.e., round-off errors accumulate) for values of $Kh/S \left[1/(\Delta x)^2 + 1/(\Delta y)^2\right]\Delta t > 1/2$. Figure 7 may be used to determine the maximum value of Δt for specific values of Δx and Kh/S, when Δx equals Δy. For the example shown by the dotted lines, if $Kh/S = 2.50$ ft^2/sec, and $\Delta x = \Delta y = 1320$ feet, the maximum time step to assure stability with the explicit method is approximately two days.

Many different ways of constructing a finite-difference representation of Equation 3 are available. Common designations for the equations or methods include:

1. Explicit Method
2. Crank-Nicolson Implicit Method
3. Alternating Direction Implicit Procedure
4. Alternating Direction Explicit Procedure.

These and other methods are discussed by Quon, et al (1965, 1966) as applied to the analysis of petroleum reservoirs. Crank and Nicolson (1947) applied their finite-difference development to heat conduction problems and showed that the method reduced the volume of calculation and was convergent and stable for all values of Δx, Δy, and Δt. The Crank-Nicolson method requires the solution of

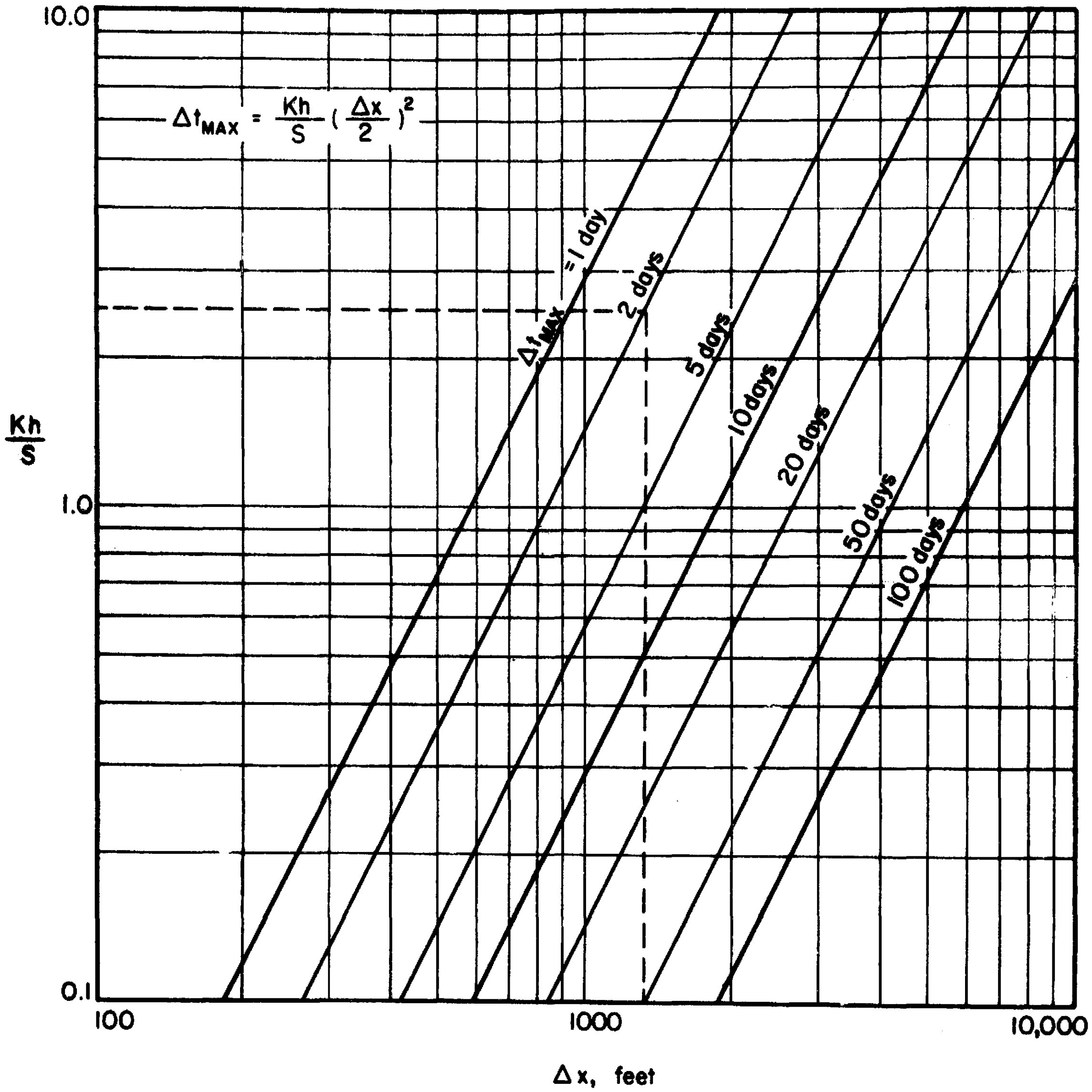


Fig. 7. Chart for determining the maximum time step for stability of explicit finite difference calculations.

(M-1)(N-1) simultaneous equations (where M = number of grid points in the y-direction, and N = number of grid points in the x-direction) for each step forward in time. Thus, for models containing many grids, use of a high speed digital computer is desirable.

Peaceman and Rachford (1955) introduced the Alternating Direction Implicit Procedure (ADIP) and applied it to petroleum reservoir analyses. They showed that the method required about 1/25th the work of an explicit solution and 1/7th the work of a Crank-Nicolson solution for a typical problem. Their technique replaces only one of the second-order derivatives, say $\partial^2H/\partial x^2$, by an implicit difference approximation, while the other second-order derivative $\partial^2H/\partial y^2$, is replaced by an explicit expression. For the next time step the implicit and explicit expressions are applied to the opposite second-order derivatives, etc. Thus, for each calculation there are (M-1) independent systems of equations, each containing (N-1) unknowns--or on the alternate step (N-1) independent systems of equations, each system involving (M-1) unknowns. Both computer time and core storage may be conserved by using this technique as compared to fully implicit methods. Irby and Arpa (1964) report successful analyses of models containing 5000 grid points utilizing ADIP.

Saul'yev (1964) and Larkin (1964) have reported on the Alternating Direction Explicit Procedure (ADEP). Quon et al (1965, 1966) state that ADEP is stable and computationally efficient.

It should be noted that the finite-difference technique can also be used for grid cells which are not rectangular or uniform in size ... California Department of Water Resources personnel (Chun and Weber, 1963; Tyson and Weber, 1964) have favored irregular polygons constructed about each well for which historical water-level data are available. The polygons are constructed by bisecting lines joining the wells, known as the Thiessen Polygon Method in other applications. In this way, cell sizes are related to the density of information which provides a built-in variable accuracy to the model comparable to the field situation. Somewhat the same results may be accomplished with rectangular grids by "focusing" with smaller Δx and Δy dimensions where field information or desired results justify the additional computational time (Bittinger, Duke, and Longenbaugh, 1967).

Description of models studied

For purposes of this study, a series of one- and two-dimensional models of stream-aquifer systems were analyzed. Groundwater flow in the one-dimensional models is restricted to right angles to the stream, whereas the downstream gradient of the aquifer and stream may be taken into consideration in the two-dimensional models. Results of analyses are reported in the following sections. One-dimensional models are identified with a three-digit number beginning with one, whereas the two-dimensional model numbers begin with a two. Detailed descriptions of the input variables and the system parameters used in each model are given in Appendixes C and E. Calculated responses, in terms of percentage outflow to the stream during 10-day and 30-day periods, are given in Appendixes D and F. All calculations were made utilizing a backward-difference, implicit representation of Equation 3, as follows:

$$AH_{i,j-1,n+1} + BH_{i-1,j,n+1} + \left(-A-B-C-D-\frac{S}{\Delta t}\right)H_{i,j,n+1}$$

$$+ CH_{i,j+1,n+1} + DH_{i+1,j,n+1} = -\frac{S}{\Delta t}H_{i,j,n} + \frac{Q_{i,j,n}}{\Delta x\ \Delta y}, \quad . . . (13)$$

where the coefficients A,B,C and D are equal to the following expressions:

$$A = \frac{(Kh)_{i,j-1,n} + (Kh)_{i,j,n}}{2(\Delta x)^2} \quad . . . . (14)$$

$$B = \frac{(Kh)_{i-1,j,n} + (Kh)_{i,j,n}}{2(\Delta y)^2} \quad . . . . (15)$$

$$C = \frac{(Kh)_{i,j+1,n} + (Kh)_{i,j,n}}{2(\Delta x)^2} \quad . . . . (16)$$

$$D = \frac{(Kh)_{i+1,j,n} + (Kh)_{i,j,n}}{2(\Delta y)^2} \quad . . . . (17)$$

Equation 13 contains five unknowns, and if reduced to a one-dimensional equation it contains three unknowns. A set of MxN equations (where M is the number of rows of width Δy and N is the number of columns of width Δx) must be solved for each time step. For the one-dimensional case only M simultaneous equations are involved. For the analyses reported herein, the classical Gaussian elimination technique was used in solving the sets of simultaneous equations.

Accuracy of results as affected by finite-difference approximation

The finite-difference procedure replaces a continuous function with a representation based upon discrete segments of both time and space. Although a finite-difference equation may be mathematically stable, the accuracy with which its solution approximates the true solution of the partial differential equation is affected by the time-step size (Δt) and the grid size (Δx and Δy). The person planning a mathematical model for a particular basin should choose time-step sizes and grid sizes which are compatible with the accuracy of the available physical data and with the accuracy desired of the results.

Comparisons of return-flow calculations made with one-day and ten-day time steps are presented in Table 2. These calculations were made utilizing a one-dimensional implicit backward-difference equation. The sets of simultaneous equations for each time step were solved by means of the Gaussian elimination procedure.

The comparisons shown in Table 2 illustrate that the largest discrepancies due to an increase in time-step size are encountered when the water table elevation is changing rapidly due to addition or withdrawal of water from the aquifer. The table also shows that the influence of time-step size is not as great for a wide aquifer (Model 161) as it is for one which is narrow (Model 158). But even for the one-half mile wide aquifer, the maximum accumulated error due to a change from a one-day time step to a ten-day time step was 3.3 percent of the water added to the aquifer. The maximum discrepancy during any one ten-day period was 2.3 percent and during any one thirty-day period (30-60 days) was 5.5 percent. In contrast, for an aquifer three miles in width calculations shown in Table 2 indicate that the maximum discrepancy during any ten-day period would be about 0.5 percent of the water added to the aquifer, and the maximum discrepancy over a thirty-day period would be only 1.0 percent. This is also the maximum accumulated error. It should be noted that these figures will vary somewhat depending upon the input conditions and the system parameters.

Because of the small differences noted between calculations made on one-day intervals and 10-day intervals, the remainder of the calculations reported in this study were made using a time-step of ten days.

Comparisons of return-flow calculations using various values for Δx and Δy are given in Table 3. As can be noted from the results in the table, the accuracy of the results obtained are not very sensitive to the size of Δx and Δy within the ranges studied. Even when the width of

Table 2. Comparison of return-flow percentages obtained from calculations using Δt = 1 day and Δt = 10 days.

			Difference				Difference	
10-day period	Model 158[a] computed with Δt=1 day (% returned)	Model 158 computed with Δt=10 days (% returned)	(per 10-day period)	(Accum)	Model 161[a] computed with Δt=1 day (% returned)	Model 161 computed with Δt=10 days (% returned)	(per 10-day period)	(Accum)
0-10	4.0	5.0	-1.0		0.7	0.9	-0.2	
10-20	11.2	12.2	-1.0	-2.0	1.9	2.2	-0.3	-0.5
20-30	23.9	25.2	-1.3	-3.3	4.3	4.8	-0.5	-1.0
30-40	24.3	22.0	+2.3	-1.0	4.8	4.7	+0.1	-0.9
40-50	17.8	16.0	+1.8	+0.8	4.3	4.2	+0.1	-0.8
50-60	9.7	8.3	+1.4	+2.2	3.4	3.2	+0.2	-0.6
60-70	4.6	4.7	-0.1	+2.1	2.8	2.7	+0.1	-0.5
70-80	2.3	2.7	-0.4	+1.7	2.5	2.4	+0.1	-0.4
80-90	1.1	1.5	-0.4	+1.3	2.2	2.2	0.0	-0.4
90-100	0.6	0.9	-0.3	+1.0	2.0	2.0	0.0	-0.4
100-110	0.3	0.5	-0.2	+0.8	1.9	1.9	0.0	-0.4
110-120	0.1	0.3	-0.2	+0.6	1.8	1.8	0.0	-0.4
120-130	0.0	0.2	-0.2	+0.4	1.7	1.7	0.0	-0.4
130-140	0.0	0.1	-0.1	+0.3	1.6	1.6	0.0	-0.4
140-150	0.0	0.1	-0.1	+0.2	1.5	1.5	+0.1	-0.3
150-160	----	----	----	----	1.5	1.5	0.0	-0.3
160-170	----	----	----	----	1.4	1.4	0.0	-0.3
170-180	----	----	----	----	1.4	1.4	0.0	-0.3

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[a] Model 158 represents an aquifer 1/2-mile wide and Model 161 represents an aquifer 3-miles wide, other input variables and system parameters remaining the same. See Appendix C for detailed description of models.

Table 3. Comparison of return-flow percentages obtained from calculations using Δy = 66 feet and Δy = 660 feet.

10-day periods	Model 158[a] with Δy=66 ft (% returned)	Model 158 with Δy=660 ft (% returned)	Difference (per 10-day period)	Difference (Accum.)
0-10	5.1	5.0	+0.1	
10-20	12.4	12.2	+0.2	+0.3
20-30	26.0	25.2	+0.8	+1.1
30-40	21.9	22.0	-0.1	+1.0
40-50	15.9	16.0	-0.1	+0.9
50-60	8.1	8.3	-0.2	+0.7
60-70	4.6	4.7	-0.1	+0.6
70-80	2.6	2.7	-0.1	+0.5
80-90	1.5	1.5	0.0	+0.5
90-100	0.9	0.9	0.0	+0.5
100-110	0.5	0.5	0.0	+0.5
110-120	0.3	0.3	0.0	+0.5
120-130	0.2	0.2	0.0	+0.5
130-140	0.1	0.1	0.0	+0.5

[a] See Appendix C for detailed description of Model 158.

the aquifer was divided into only four parts, the maximum difference during a 10-day period compared to an aquifer divided into 40 parts was 0.8 percent. Similar results were found in the two-dimensional models. Fortunately, the errors due to time-step size and grid size tend to counteract each other. Therefore, in the remainder of the models studied and reported herein, the standard size for Δy in the one-dimensional models was 660 feet. The standard sizes for Δx and Δy in the two-dimensional models were 2,640 feet and 1,320 feet, respectively.

A comparison of analytical and finite-difference solutions--using these grid sizes and a 10-day time step--is given in Table 4. Both calculations are for a two-mile wide aquifer which receives a uniform input Q at time zero, and none thereafter. The results are given in percent of the water added which returns to the stream during each 10-day period. The analytical solution is for the linear, one-dimensional partial differential equation, whereas the finite-difference equation is set up to approximate the nonlinear form (variable Kh). As would be expected, the most discrepancy between the two solution techniques occurs during the first 10 days when the water table is changing most rapidly. During the first 30 days the discrepancy is only 1.7 percent of the water applied, and becomes essentially zero within any 10-day period after 50 days.

Table 4. Comparison of return-flow percentages obtained from analytical and finite-difference calculations. Model 153[a]

			Difference	
10-day period	Analytical solution (% returned)	Finite-difference solution (% returned)	(per 10-day period)	(accum.)
0-10	15.7	13.1	+2.6	
10-20	6.5	7.1	-0.6	+2.0
20-30	5.0	5.3	-0.3	+1.7
30-40	4.2	4.4	-0.2	+1.5
40-50	3.7	3.8	-0.1	+1.4
50-60	3.4	3.4	0.0	+1.4
60-70	3.1	3.1	0.0	+1.4
70-80	2.9	2.9	0.0	+1.4
80-90	2.7	2.7	0.0	+1.4

[a] See Appendix C for detailed description of Model 153.

Basic assumptions

Several basic assumptions are common to all of the models studied. These include (1) a free interchange between groundwater and surface water--influenced only by the relative elevations of the two, (2) groundwater flow between finite-difference cells is horizontal and uniform throughout the saturated thickness, and (3) a single unconfined aquifer is modeled which is bounded on the sides and bottom by an impermeable formation.

STREAM-AQUIFER SYSTEM BEHAVIOR

As shown in Figure 5, the response behavior of a stream-aquifer system may be influenced by many input variables and the interaction of many system parameters. The number of possible combinations of these factors existing in nature is infinite--not only in terms of magnitudes of the factors, but also in variations in both time and space. Even for rather simple stream-aquifer systems, it is quite unlikely that an investigator can depend on there being a unique combination of inputs and system parameters which will produce a particular response. In addition, it is rarely economically feasible to quantitatively evaluate many of the input variables and system parameters with precision. It is, therefore, quite important that an investigator designing and developing a model of a stream-aquifer system be aware of the response behavior as influenced by these variables and parameters. Knowledge of the response sensitivity can help avoid needless time and expense expended on collecting superfluous information.

Influence of Input Variables

As discussed previously, the amount of water added to the system and its distribution in both time and space influences the behavior of the response variables. Analyses were made to determine the sensitivity of response to amounts of water added, the time distribution of the addition, and the areal distribution of the water added.

Effect of total input Q

Models 101, 151, and 152 were identical except for the total amount of water added to the groundwater system. These models simulated an aquifer two miles wide with a water application pattern extending over a 50-day period. A comparison of calculated return flow to the river for these three models is given in Table 5. This tabulation shows

Table 5. Comparison of return-flow percentages obtained from calculations using different quantities of water added to the aquifer.

Time	Model 151 net Q=½foot[a] (% returned)	Model 101 net Q=1 foot[a] (% returned)	Model 152 net Q=2 feet[a] (% returned)
0-10 days	1.3	1.3	1.3
0-30 days	11.9	11.9	12.0
0-60 days	29.9	30.0	30.4
0-120 days	48.8	49.2	50.0
0-360 days	82.9	83.1	83.8

[a] Net Q added uniformly to the aquifer in the following time patterns: 10% during first 10-day period, 20% during second 10 days, 40% during third 10 days, 20% during fourth 10 days, and 10% during fifth 10 days. See Appendix C for further description of Models 101, 151, and 152.

that a nearly direct relationship occurred between the total amount of water applied and the timing of water returning to the stream from the aquifer. In other words, within a reasonable range the percent of error that may be involved in estimating the amount of deep percolation of irrigation water to the groundwater system is reflected in a like percentage of error in the estimation of the return flow at any point in time. The small discrepancies shown in Table 5 are probably because a larger area of flow is available for the groundwater in cases of larger amounts of water added. For instance, the two feet of water application in Model 152 represented ten feet of water in the aquifer or an additional 20 percent of flow area above the original saturated thickness of 50 feet. On the other hand, the one-half foot of water added to Model 151 represented 2½ feet of water in the aquifer, an increase of only 5 percent above the original 50-feet of saturated thickness.

The other response parameter, the fluctuation of the water table, is especially sensitive to the amount of water added or withdrawn from the aquifer. The response is magnified by a factor of 1/S, usually equal to from four to six for most aquifers. Therefore, if an error of one foot is made in estimating the amount of deep percolation of irrigation water to the groundwater system, an error of four to six feet will be made in the estimation of the water table response.

Effect of time distribution of input Q

Response of a stream-aquifer system, in terms of the groundwater return flow to the river, appears to be rather insensitive to the time distribution of the water applied. Table 6 compares three models in which the water input to the aquifer varied with time, with the total water added being identical. The time distribution patterns of water added to the aquifer in models 201C and 201B were used to simulate irrigation periods of 50 and 80 days. As can be noted from Table 6, the water applied during any one 10-day period varied considerably, but the return flow calculations show only minor differences. Even if all of the water is applied instantaneously (as in Model 201A), the difference in the return flow pattern compared to applications over 50- and 80-day periods is amazingly small. For the conditions depicted in Table 6, it appears that soon after all of the water has been added the return flow pattern is essentially the same. Therefore, unless one wishes to study the return flow pattern during the time of water addition, a great deal of concern about duplicating the prototype time distribution of water application may not be justified.

Effect of areal distribution of input Q

All of the models discussed above received a uniform addition of water to the aquifer over its entire surface. Many field situations occur in which an area next to the river is not irrigated. This is usually because of a flood

Table 6. Comparison of return-flow percentages obtained from calculations using same total net Q but different time distributions.

Time	Model 201C[a] (% returned)	Model 201B[a] (% returned)	Model 201A[a] (% returned)
0-10 days	1.2	1.2	
0-30 days	11.4	10.9	13.0
0-60 days	29.7	26.3	30.5
0-120 days	49.1	47.6	49.4
0-360 days	83.1	82.7	82.9

[a] Portion of total net Q added during 10-day intervals as follows:

	Model 201C	Model 201B	Model 201A
0-10 days	10%	10%	---
10-20 days	20%	30%	---
20-30 days	40%	20%	100%
30-40 days	20%	15%	---
40-50 days	10%	10%	---
50-60 days	---	5%	---
60-70 days	---	5%	---
70-80 days	---	5%	---

See Appendix E for further description of Model 201.

hazard, or a consistently high water table. Models 102, 103 and 104 were designed to determine the influence of water added to varying portions of the aquifer. As shown in Figure 8, Model 102 represented a situation in which a strip one-fourth the width of the total aquifer, lying next to the river, was not irrigated. Likewise, Models 103 and 104 represented situations in which this strip was 50 percent and 75 percent of the total aquifer width. In Figure 8 it can be seen that widening the strip which received no additon of water caused a delay in the peak return flow and reduced its magnitude compared to the total amount of water added. For instance, with a full application of water over the entire aquifer (as represented in Model 101), the peak return flow occurred at approximately 30 days after the beginning of water application. Model

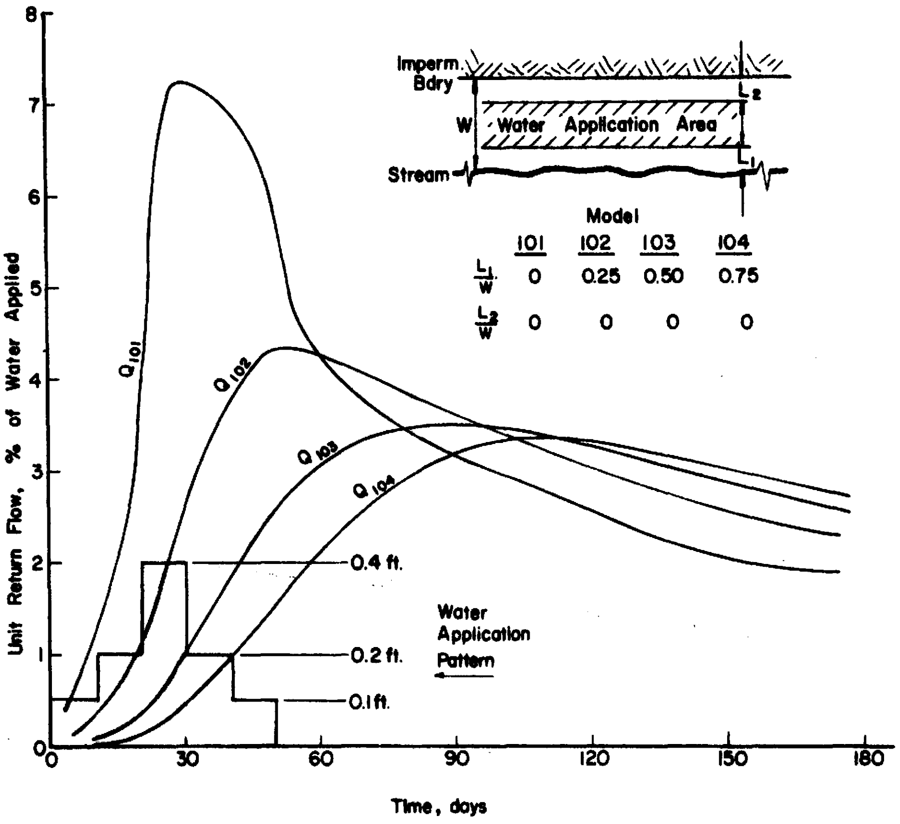


Figure 8. Pattern of percentage return flow as influenced by location of water application area in respect to the stream.

Model 102 shows a peak at 50 to 60 days, Model 103 at 80 to 90 days, and Model 104 at 100 to 110 days. The return flow during the peak 10-day period for these models was 7.2 percent for Model 101, 4.3 percent for Model 102, 3.5 percent for Model 103 and 3.4 percent for Model 104. These are percentages of the water added to the aquifer in each case.

Models 105 through 109 were also used to study the effect of water added at different locations in the aquifer. Using the basic Model 101 as a reference, Figure 9 graphically summarizes the return-flow response behavior due to various application area situations. Each curve shown in Figure 9 was obtained by dividing (1) the percent of water added to the application area which returned to the stream during each time period by (2) the percentage returned during comparable time periods in Model 101. Thus, the ordinate of these curves represents the factor by which one should multiply the return flow calculated for an aquifer receiving water over its entire area to convert it to a situation in which only part of the aquifer receives water. It is noticeable that these curves reverse their positions relative to one another and cross the unity line in approximately 90 to 100 days for the situations studied. The timing of this characteristic would undoubtedly be different for different input Q conditions and different system parameters, particularly the hydraulic characteristics of the aquifer.

Models 229 and 230 were utilized to study the return flow response caused by randomly located water application areas. Model 229 represented an aquifer area of 2 miles by 10 miles. This was divided into 160 grid cells. Twenty models were constructed, each having the irrigated area designated by a random process in which each cell had a 0.75 probability of being chosen. As shown in Table 7, the percent of the total area irrigated in the twenty models ranged from 70 to 81.2, with a mean of 76.0 and a standard

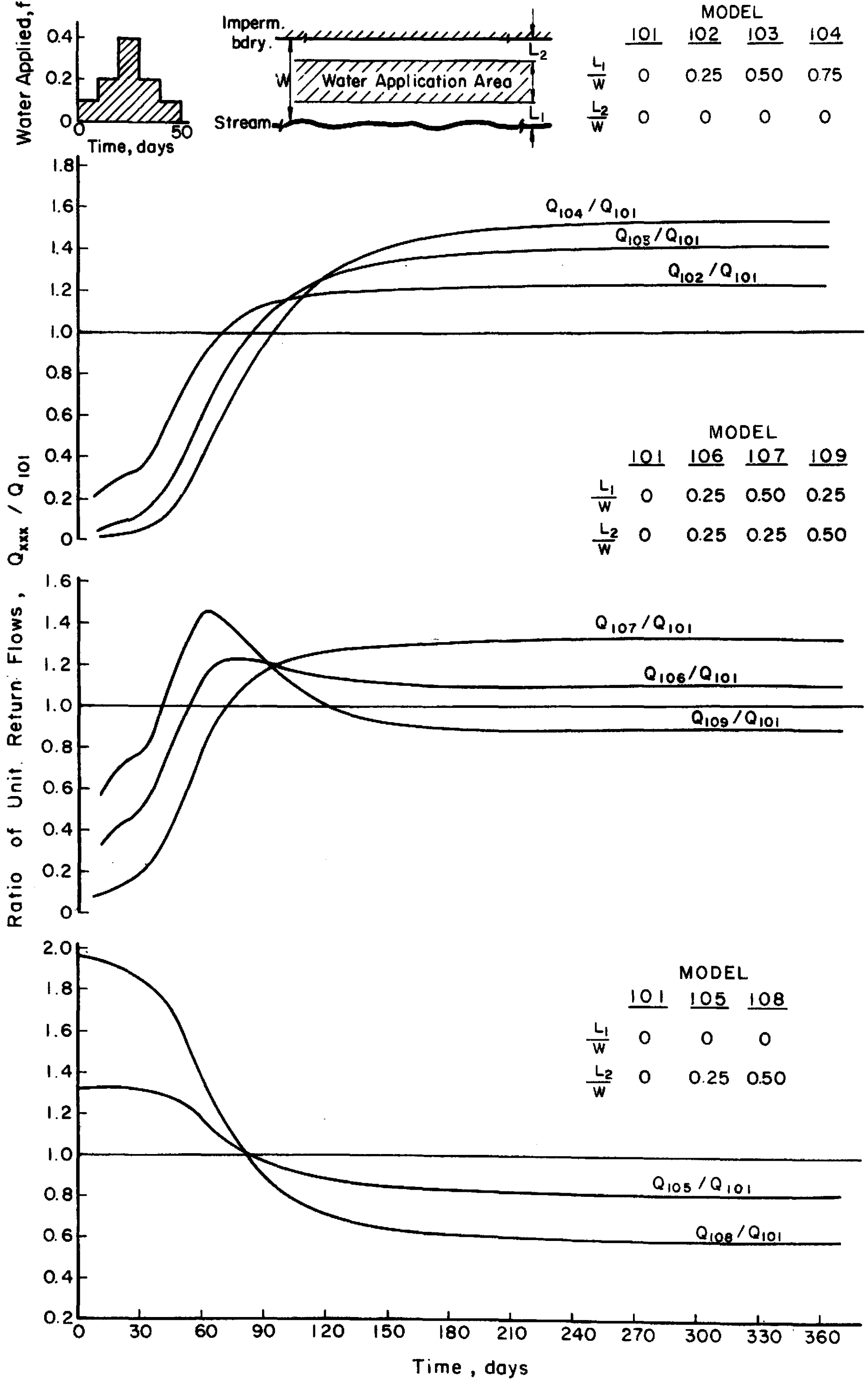


Fig. 9. Comparison of return-flow patterns from various water application area situations.

Table 7. Return-flow characteristics of aquifers receiving water on approximately 75% of the surface area.

Model 229 (Composite of 20 models)[a]

Application area (% of total area)

Range	Mean	Standard deviation
70.0 to 81.2	76.0	3.0

Return flow (% of water added)

Time	Range	Mean	Standard deviation
0-10 days	1.1 to 1.4	1.3	0.1
0-30 days	10.5 to 12.6	11.6	0.5
0-60 days	27.8 to 31.8	29.8	1.0
0-120 days	47.2 to 50.9	49.0	0.8
0-360 days	82.4 to 83.6	83.0	0.3

[a] See Appendix for full description of Model 229.

deviation of 3.0. The return flow from each model was calculated in terms of the percent of water added to each model. Table 7 shows a summary of results for various time periods in terms of the range, the mean, and the standard deviation.

Model 230 was similar to Model 229, except that each grid cell was given a 0.50 probability of receiving water. Of the twenty models studied, the percentage of area receiving water ranged from 41.9 to 58.1. As shown in Table 8, the mean return flow percentages from Model 230 were very similar to that of Model 229, except that the ranges and standard deviations were somewhat larger. As would be expected, the variance of the return flows within the twenty models was strongly influenced by the location of irrigated areas close to the stream. These results do show, however, that if the water application areas are fairly uniformly distributed over the aquifer, the percentage return flow at any time is very little different from that of an aquifer which received a uniform distribution of water over all of its area.

Table 8. Return-flow characteristics of aquifers receiving water on approximately 50% of the surface area.

Time	Range	Mean	Standard deviation
Model 230 (Composite of 20 models)[a]			
Application area (% of total area)			
	41.9 to 58.1	50.5	4.0
Return flow (% of water added)			
0-10 days	1.0 to 1.6	1.3	0.1
0-30 days	9.2 to 14.1	11.6	1.1
0-60 days	25.2 to 34.1	29.6	2.0
0-120 days	44.7 to 52.5	48.7	1.8
0-360 days	81.4 to 84.1	83.7	0.6

[a] See Appendix E for full description of Model 230.

Influence of System Parameters

Several one-dimensional and two-dimensional models were studied to determine the influence of various system parameters upon response characteristics. Results of these studies are discussed in the following sections.

Effect of aquifer characteristics

As indicated in Figure 5, the aquifer characteristics of importance include (1) permeability, (2) specific yield, (3) aquifer width, and (4) saturated thickness. The permeability, K, the specific yield, S, and the saturated thickness, h, are often combined to form an aquifer constant, α:

$$\alpha = \frac{Kh}{S} \quad \ldots\ldots\ldots\ldots\ldots \quad (18)$$

The aquifer constant has dimensions of L^2/T when the individual factors are expressed in fundamental foot-pound-second units. Utilizing principles of dimensional analysis, the following functional relationship may be derived:

$$q = f\left(\frac{\alpha t}{W^2}\right) \quad \ldots\ldots\ldots\ldots (19)$$

In Equation (19), q represents the portion of the net Q added to the aquifer which returns to the stream in time t, and W represents the aquifer width.

The importance of the dimensionless parameter $\alpha t/W^2$ is borne out by the exact solutions which have been derived for the linear partial differential equations describing the return-flow response to additions or withdrawals of water from an aquifer. Such an exact solution, for an idealized aquifer receiving a uniform application of water at time 0, is given below, adapted from Glover (1964).

$$q = 1.0 - \frac{8}{\pi^2} \sum_{n=1,3,5\ldots}^{n=\infty} \frac{\exp\{-(\frac{n\pi}{2})^2 (\frac{\alpha t}{W^2})\}}{n^2} \quad \ldots (20)$$

Another exact solution adapted from Glover (1964) for the case of a canal leaking water to an aquifer or a well pumping water from an aquifer is as follows:

$$q = 1.0 - \frac{2}{\sqrt{\pi}} \int_0^{\frac{x}{\sqrt{4\alpha t}}} e^{-u^2} du \quad \ldots\ldots\ldots (21)$$

The x in Equation (21) represents the distance from the canal or well to the stream, and the u is a variable of integration. The integral in Equation (21) is a form of the standard normal probability function, tabulations of which are widely available.

Equations (20) and (21) describe groundwater flow to (or from) the stream with time after an instantaneous addition (or withdrawal) of water at the initial time 0. Most of the one-dimensional models analyzed in this study had water added to the aquifer over a period of time and are not strictly comparable to the above equations. However, Model 153 simulated a condition of water applied only during the first 10-day period. Figure 10 shows a comparison between the solutions of Equation (20) and finite-difference calculations for Model 153. These curves are plotted using the dimensionless parameter $\sqrt{\alpha t}/W$ versus the percent of the total quantity of water added returning prior to time t. Model 153 underestimated the return flow as compared to that obtained from Equation (20). This is as would be expected because of the application of water being spread over 10 days compared to an instantaneous application at the beginning of the period. However, the differences are minor compared to inaccuracies that are generally involved in the estimation of other factors used in the calculation.

To affirm that the constant, α, is a true aquifer characteristic, Model 137 was compared with Model 101. Model 137 had a permeability twice that of Model 101, but a specific yield also twice as large so that the value of α was the same as used in Model 101. Results of these and similar analyses produced identical return-flow responses, as can be noted in Appendix D.

Permeability magnitude. The influence of the magnitude of permeability upon the return-flow response is illustrated in Figure 11. This figure compares Models 101, 125, 126, 127, and 128. The latter four models are compared with the basic model by dividing the calculated return flows by those obtained for Model 101. Model 128 had a permeability five times that of Model 101, but its return flow ranged from 2.3 times to 0.3 times that of Model 101. Model 127, which had a permeability twice that of 101, ranged only from 1.4 times the outflow of the basic model to about 0.5 at the end of the year. Models 125 and 126 had permeabilities of one-tenth and one-half the basic model and show a percentage outflow less than Model 101 for most of the one-year period. An important feature to note from Figure 11 is that if one overestimates the permeability of an aquifer, his calculation of return flow will be too high during a period of

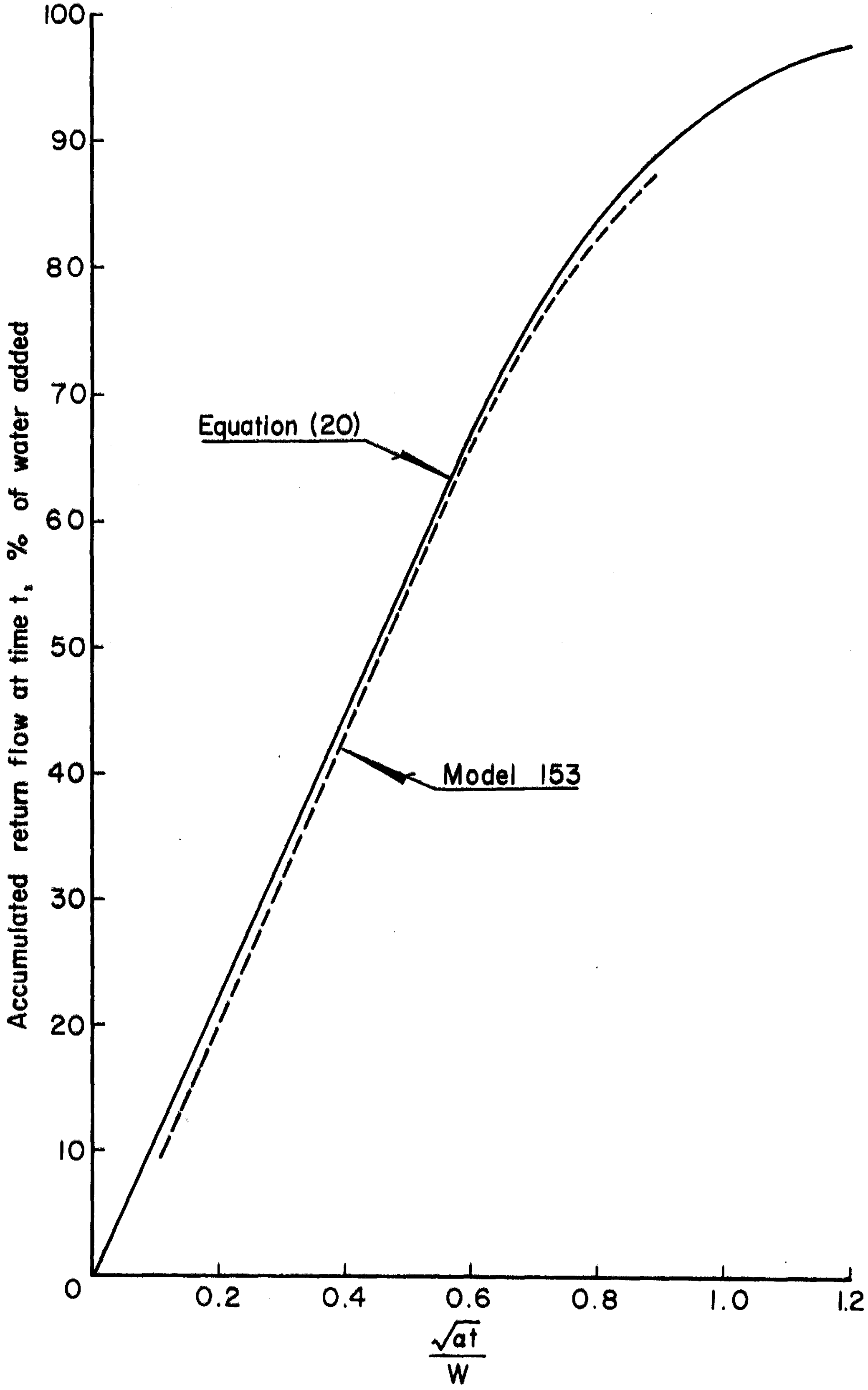


Figure 10. Comparison of solution of Equation (20) with results from Model 153.

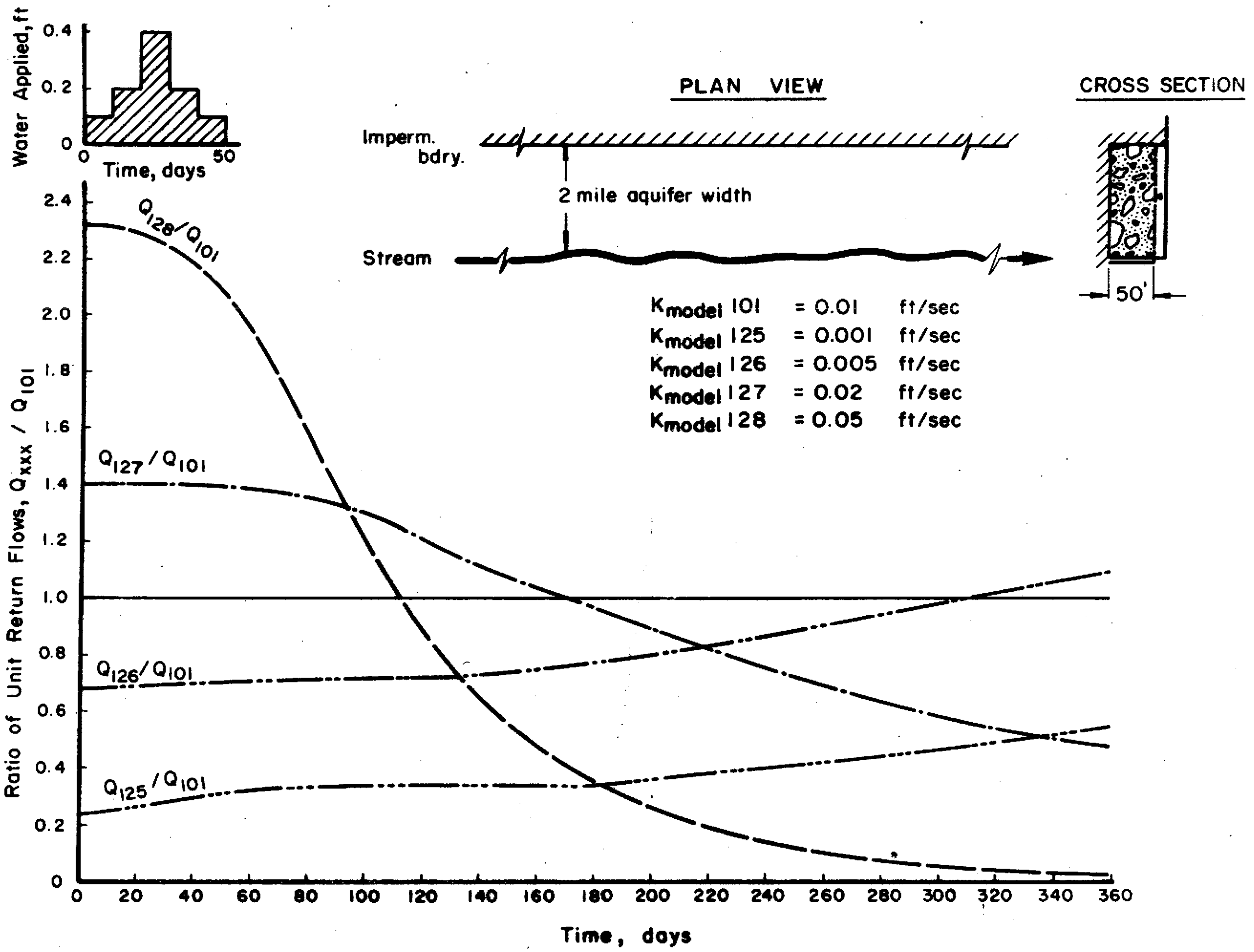
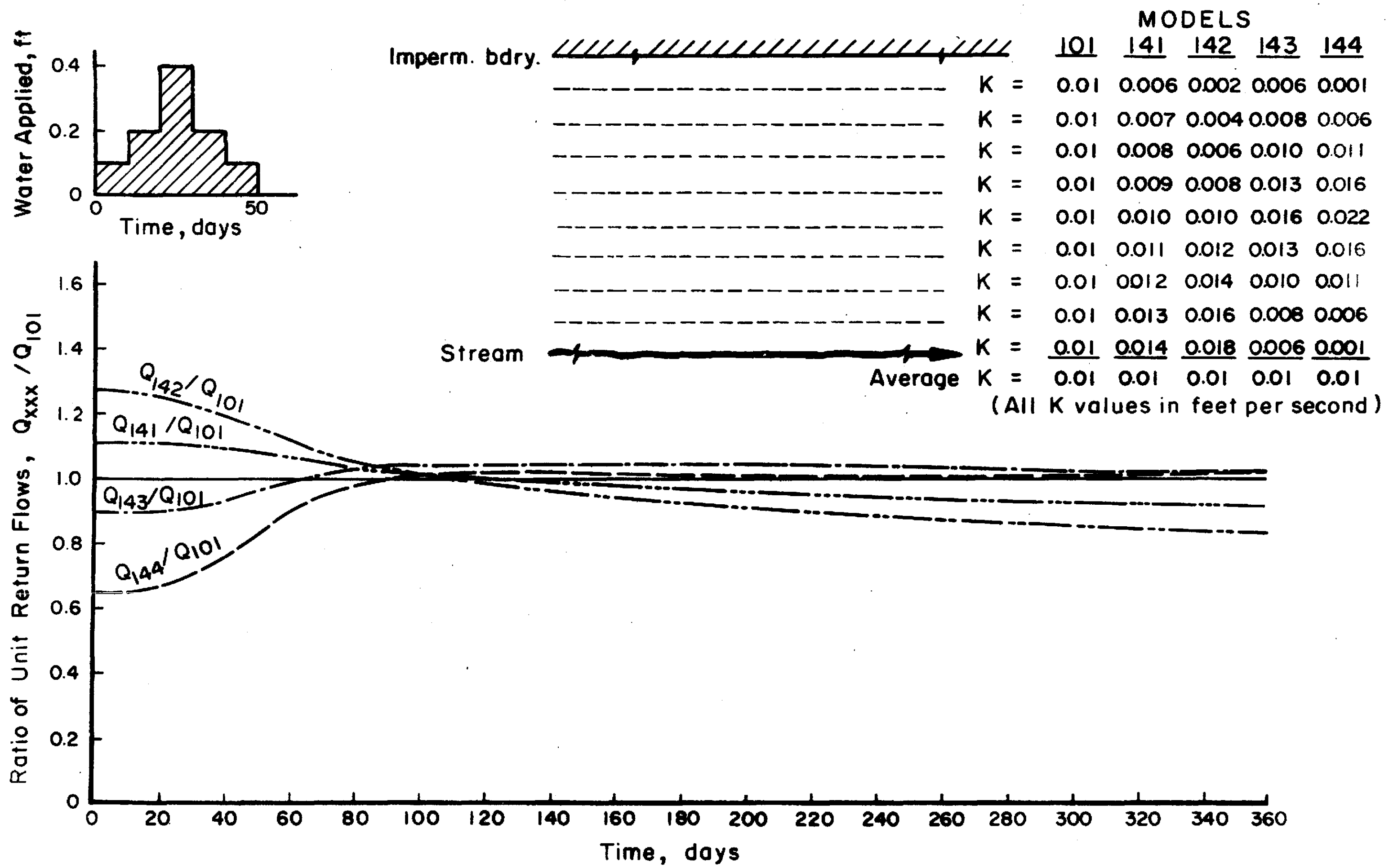


Figure 11. Influence of permeability magnitude on return-flow response

time immediately after application of water and too low during the latter part of the calculation. If the permeability is estimated too low, the tendency is for the return flow calculations to be too low throughout the entire period of study. It is also noticeable that a 100-percent error in estimation of permeability will not result in an error of that magnitude in estimating the return flow. In addition, if several years of calculations are made, the error tends to become smaller.

Permeability distribution. Models 141, 142, 143, and 144 were designed to study the effect of permeability distribution in aquifers. These models represented aquifers two miles in width in which the permeability varied according to the chart shown in Figure 12. The arithmetic mean permeability of each aquifer was the same, 0.01 feet per second. The return flow response calculated for these models is compared to Model 101 in Figure 12. The ratios of return flows for each of the four models to the return flows calculated for Model 101 show that the major differences occur during the first 50 or 60 days (or essentially during the period of water addition to the aquifer). Model 141 simulated an aquifer in which the permeability was less than average at the impermeable boundary and greater than average at the stream. The range of permeability was from 0.006 to 0.014 feet per second. The maximum ratio between the return flows from Model 141 and Model 101 was less than 1.2. Model 142 had a similar permeability gradient but a wider range--from 0.002 feet per second at the impermeable boundary to 0.018 feet per second at the stream. The maximum ratio for this condition was 1.3. The extreme permeability distribution studied, that in Model 144, resulted in a ratio of 0.65 at the beginning of the period, becoming near 1.0 after about 80 days. These results seem to indicate that a fairly wide areal distribution



MODELS

	101	141	142	143	144
K =	0.01	0.006	0.002	0.006	0.001
K =	0.01	0.007	0.004	0.008	0.006
K =	0.01	0.008	0.006	0.010	0.011
K =	0.01	0.009	0.008	0.013	0.016
K =	0.01	0.010	0.010	0.016	0.022
K =	0.01	0.011	0.012	0.013	0.016
K =	0.01	0.012	0.014	0.010	0.011
K =	0.01	0.013	0.016	0.008	0.006
K =	0.01	0.014	0.018	0.006	0.001
Average K =	0.01	0.01	0.01	0.01	0.01

(All K values in feet per second)

Figure 12. Influence of permeability distribution on return-flow response

of permeability may be safely classified into one average value for simulation of an aquifer.

The two-dimensional models 208, 209, 210, and 211, were developed to determine if slope in the bedrock and initial water table would result in different return flow values. These conditions made little difference in the response so the results are not shown here. It should be commented, however, that if in field conditions a stream meanders around a valley which has high and low permeability areas, or directional permeability such as in Model 211, the return flow pattern along the stream may vary considerably.

Aquifer width. Models 159, 101, 161, 162, and 163 were identical except for width of the aquifers. The widths simulated by these models were 1, 2, 3, 4, and 5 miles, respectively. Graphs of the results obtained from these five models are shown in Figure 13. It will be noted that a distinct similarity in shape of the five curves exists, but they do not superimpose over one another when plotted against the dimensionless parameter, $\sqrt{\alpha t}/W$. This figure illustrates that as the aquifer width is increased, the peak 10-day percentage return flow is reduced in direct proportion. Also the location of the peak on the abscissa scale reduces in direct proportion to the increase in aquifer width. Thus, the following two relationships can be obtained:

$$\text{peak 10-day \% return flow} = \frac{14.5}{\text{aquifer width in miles}} \quad \ldots . (23)$$

$$\text{peak 10-day \% return flow} = \frac{\sqrt{\alpha t}}{176(\text{aquifer width in miles})} \quad \ldots . (24)$$

These equations are applicable only to the input Q time distribution pattern used in these models, but similar relationships may be derived for other input Q conditions.

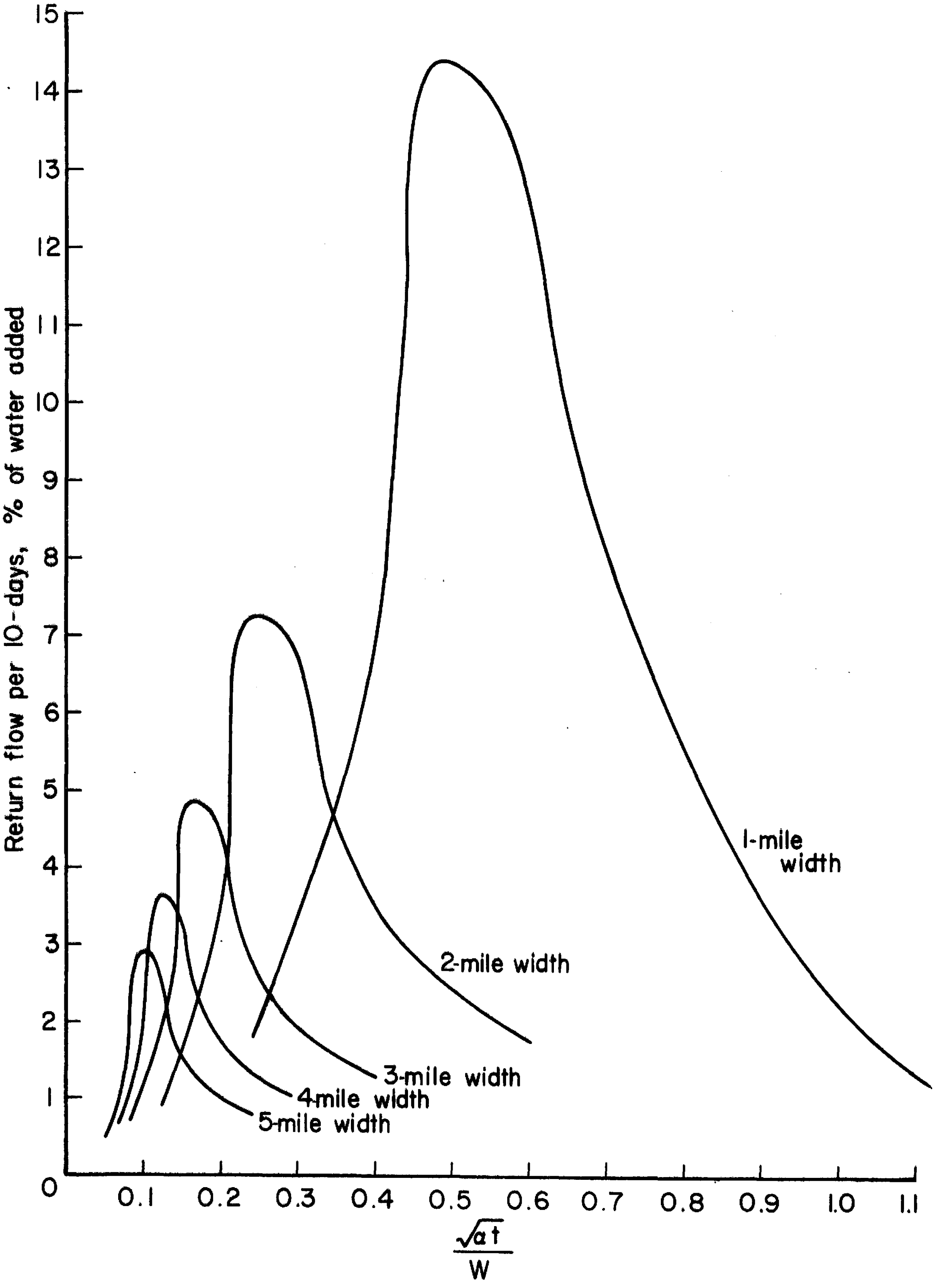


Figure 13. Influence of aquifer width on return-flow response.

Effect of boundary conditions

Because field situations rarely occur in which boundaries are uniform and geometrically simple, several models were studied to determine the effect of converging and diverging lateral boundaries and of different configurations of the bedrock underlying the aquifer.

Lateral boundaries. Models 221 and 222 were utilized to study diverging and converging lateral boundaries, respectively. Both of these models simulated an aquifer averaging two miles wide but in which the lateral boundary either diverged or converged in respect to the river at the rate of one mile per five miles of valley length. In each model the bedrock sloped toward the river and downstream at the rate of 8 feet per mile. The return-flow response from these models is compared with Model 206 in Figure 14. Model 206 was an otherwise identical model with parallel boundaries. The area of water application was the same for all three models. The return flow response from the model having diverging lateral boundaries continually decreased compared to that of the parallel boundary model. The ratios between results from Model 221 and Model 206 range from 0.99 at the end of the first 10-day period to 0.72 at the end of a year. Similarly, the ratios for the converging boundary case ranged from slightly less than 1.0 for about 140 days then increased to 1.4 by the end of a year. The effect of the converging boundary was to force additional groundwater to the stream, the amount increasing with time. It is likely that the long-term effect would be considerably more than indicated in Figure 14.

Bedrock configuration. Models 146, 147, and 148 were used to study the effect of different bedrock configurations upon the return flow response. The average saturated thickness was 50 feet, and the aquifer width 2 miles. Model 146 simulated an aquifer in which the bedrock sloped at a rate of 8 feet per mile toward the stream (the saturated thickness

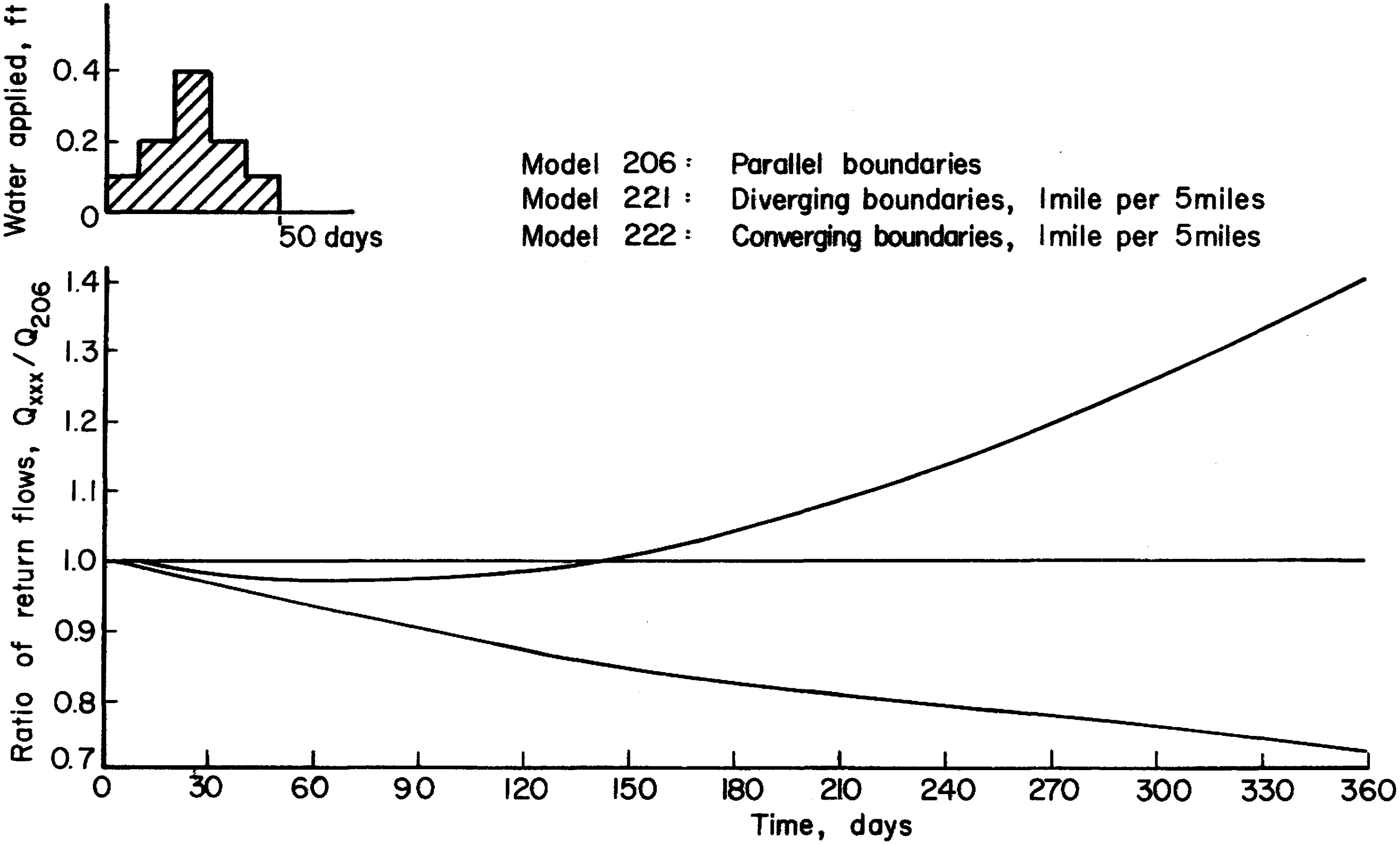


Figure 14. Influence of lateral boundaries on return-flow response.

ranged from 41.5 feet at the impermeable boundary to 58.0 feet at the stream). Model 147 simulated an aquifer in which the slope of the bedrock was away from the stream at a rate of 8 feet per mile (the saturated thickness ranged from 58.5 feet to 42.0 feet). Model 148 simulated an aquifer in which the deepest part existed midway between the stream and the impermeable boundary. The slope of the bedrock toward the deepest part of the aquifer was at a rate of 16 feet per mile (the saturated thickness ranged from 57.0 feet to 43.0 feet).

Results obtained from Models 146, 147, and 148 are compared with Model 101 (horizontal bedrock and 50-foot saturated thickness) in Table 9. Although saturated thicknesses deviated as much as 17 percent from the average of 50 feet, the return-flow responses varied less than 3 percent over a year's period from that obtained under horizontal bedrock conditions. These results indicate that extensive subsurface exploration to determine bedrock elevations may not be justified in many instances.

Effect of initial conditions

Except for Models 221 and 222, all of those discussed heretofore were simulations beginning with a horizontal water table at the same elevation as the stream level at time 0. This is an idealization of what normally is found in field conditions. Therefore, a combination of Model 206 and Model 213 was compared with Model 204 in Table 10 to determine the influence on the calculated response of a water table initially sloping toward the river and downstream.

Model 204 simulated a 2-mile wide aquifer in which a 50-day addition of water was applied to an initially level water table. Model 206 was a similar aquifer except that the initial water table and bedrock surfaces sloped toward the river and downstream at the rate of 8 feet per mile. Model 213 had water table and bedrock conditions identical to Model 206, but no water was added to it. Therefore, in Model 213 the initially sloping water table was allowed to drain to the stream with no additions or withdrawals. The difference between the return flow response measured in Models 206 and 213 is compared to that measured in Model 204 in Table 10. This shows that results obtained by superposition were somewhat larger but quite comparable to results obtained by direct calculation. Superposition can be a useful technique in modeling, often considerably reducing the number or runs which one needs to make. It should be pointed out that the more nonlinear a system is (such as one with a very thin aquifer), the more error that will be imposed by utilizing superposition.

Table 9. Comparison of return-flow percentages obtained from calculations using various configurations of the bedrock.

Time	Model 101[a] (% returned)	Model 146[a] (% returned)	Model 147[a] (% returned)	Model 148[a] (% returned)
0-10 days	1.3	1.4	1.2	1.2
0-30 days	11.9	12.9	11.0	11.1
0-60 days	30.0	31.8	28.0	28.5
0-120 days	49.2	51.4	46.4	47.5
0-360 days	83.1	84.9	80.7	82.1

[a] See Appendix C for full description of the one-dimensional models.

Table 10. Comparison of return-flow percentages obtained from calculations for models having sloping and level initial water table surfaces.

Time	Model 206A minus Model 213A[a] (% returned)	Model 204A[a] (% returned)	Difference
0-10 days	13.8	13.0	+0.8
0-30 days	27.4	26.0	+1.4
0-60 days	40.0	37.9	+2.1
0-120 days	56.5	54.1	+2.4
0-360 days	85.1	84.8	+0.3

[a] See Appendix E for full description of the two-dimensional models.

Influence of Water Management Practices

A previous section of this report identified the water management problems, causes, and needs existing within major stream-aquifer systems in the Western United States. Several models were designed to simulate some of these water management practices, such as artificial drainage, phreatophyte control, improvement of irrigation practices, and lining of canals. Since these practices performed in a stream-aquifer situation influence the groundwater regime (and, therefore, the surface water regime) it is desirable to evaluate their influences on the system responses.

Drainage

Artificial drainage practices, whether by open ditch or closed tile lines, tend to have a significant influence upon the amount and timing of return flow to the stream in a stream-aquifer system. If the drainage water is returned directly to the stream, either by gravity or by pumping, the total quantity of water returned may be increased because of the salvage of water which may have been previously used unbeneficially by evapotranspiration. The second effect upon response is reflected in the timing and quantity of the peak return flow. Drainage practices increase the accessibility of the groundwater to the surface water portion of the system, therefore, the tendency is for the return flow pattern to have a higher peak and one which occurs earlier than that prior to installation of drainage facilities. This effect is shown in Figure 8, where if one assumes that drainage facilities are constructed along the lower edge of an irrigated area which was previously at some distance from the stream, the return flow pattern would move toward that obtained when the stream is immediately adjacent to the irrigated area.

Phreatophyte control

Because of the usual location of phreatophyte growth adjacent to stream channels, it would be expected that changes in water use by phreatophytes would be rapidly reflected in the return-flow response of the system. Models 117 and 102 are compared in Figure 15 to show this effect. Both models simulated a 2-mile wide aquifer having a 1½-mile wide irrigated area. In Model 117 the 1/2-mile non-irrigated strip next to the stream had water withdrawal by phreatophytes from a strip 660-feet wide. For comparison purposes, the withdrawal pattern was assumed to be the exact negative of the addition pattern for the irrigated area. It will be noted in Figure 15 that the model with phreatophytes experienced a negative return flow (flow from the stream to the aquifer) during the early portion of the study period, although the total water withdrawn was only one-twentieth of the water applied to the aquifer. The phreatophyte consumption both lowered and delayed the peak return flow.

Improvement of irrigation efficiency

The discussion above under the heading "Influence of Input Variables" essentially covers the effect of an increase in irrigation efficiency. Assuming that the water saved is consumptively used or applied elsewhere, the reduction in deep percolation from the irrigated fields directly influences the quantity of return flow. In other words, if the water added to the aquifer is reduced 50 percent and other factors remain the same, the amount of return flow at any time t will be reduced by 50 percent. If in addition the reduction in deep percolation occurs principally during the high application period, such as the spring months, the peak return flow may be diminished by more than 50 percent.

Lining of canals

Models 110, 111, 112, and 113 were designed to study the effect of canal seepage on the return-flow response. Each model represents a 2-mile wide aquifer with the canal located at various positions in respect to the aquifer

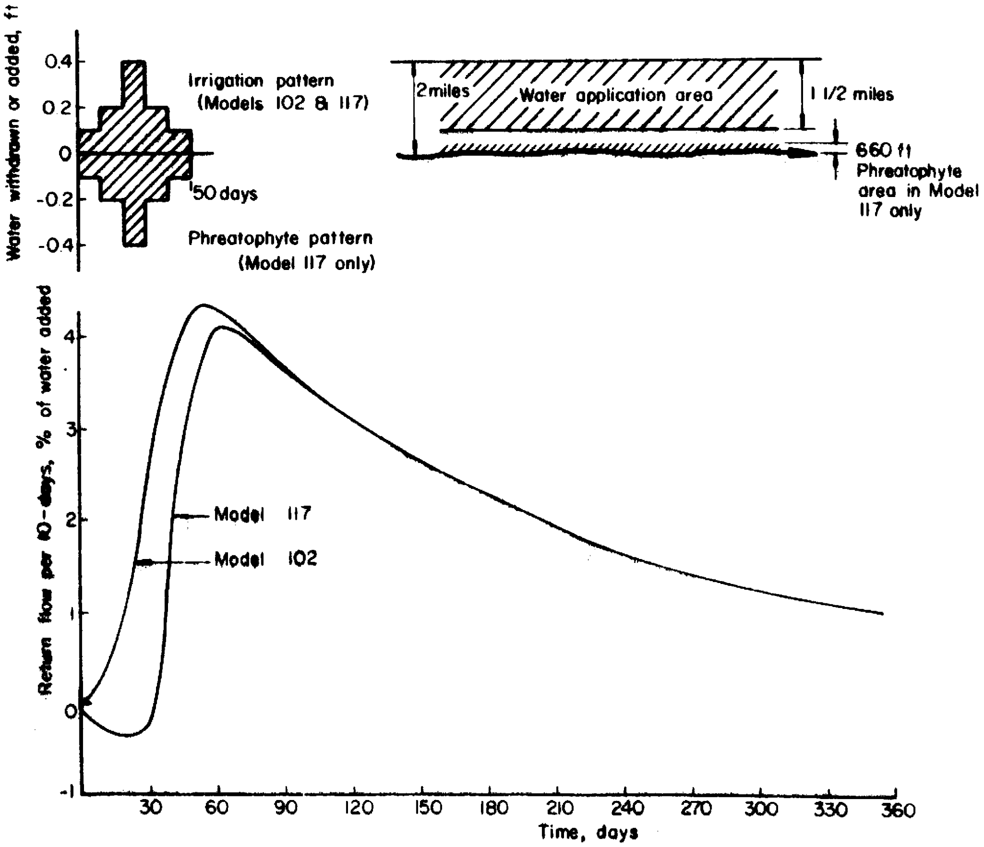


Figure 15. Influence of phreatophyte removal upon return-flow response.

boundaries and the stream. A comparison of the return flow calculated for these four models is shown in Figure 16. The curves show that the peak return-flow was about 10.7, 5.1, 3.3, and 3.2 percent of the total canal loss when located ½, 1, 1½, and 2 miles from the stream, respectively. Also of significance is the delay and flattening of the peak return flow depending on the distance of the canal from the stream.

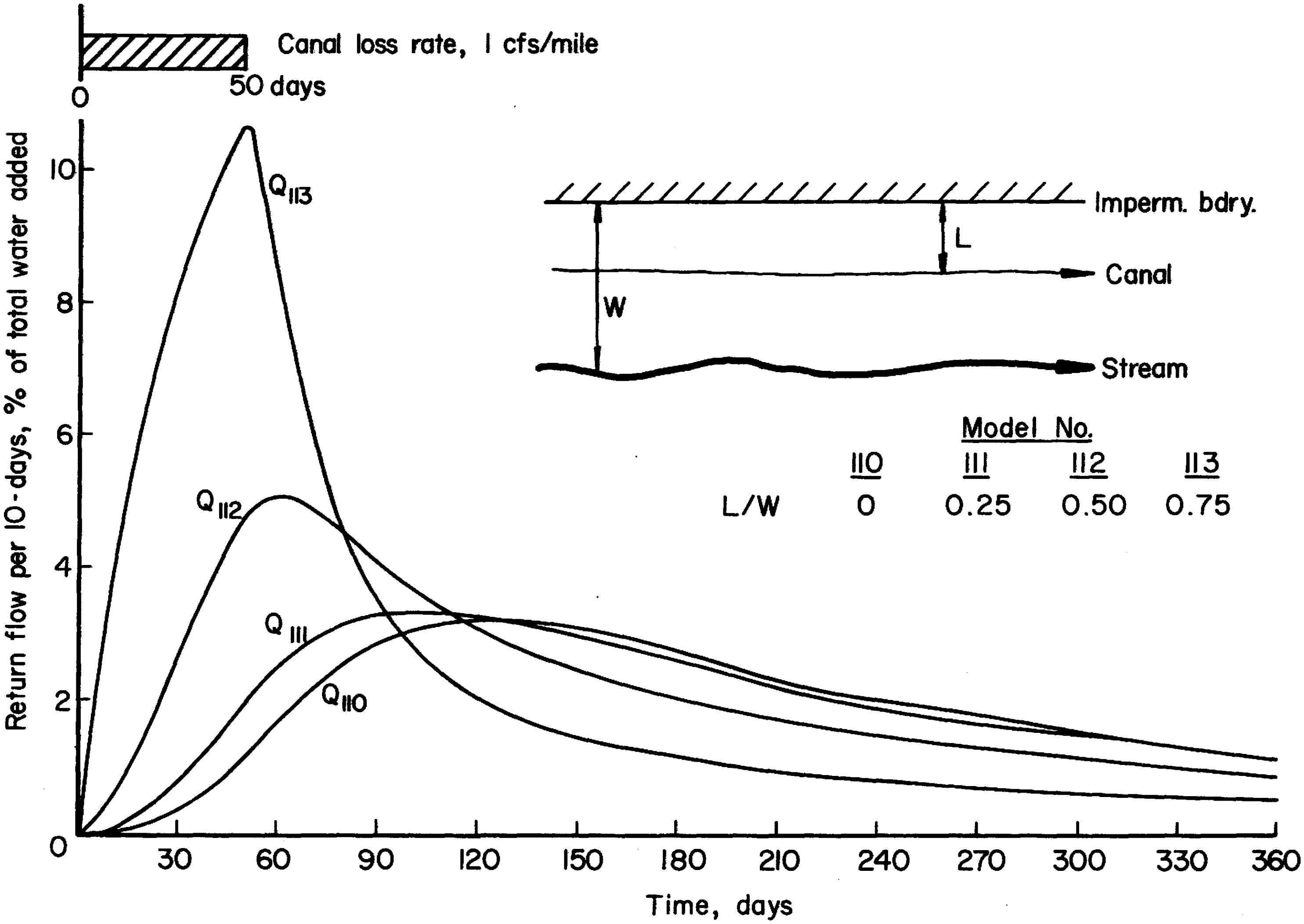


Figure 16. Influence of canal location on return-flow response.

Composite effects

Since the above-mentioned water management practices have different effects both positive and negative, upon the return flow-response of the stream-aquifer system, it is interesting to observe what the composite effect may be for a more typical situation. Model 118 simulated an aquifer 2-miles in width with an irrigated area 1½-miles wide. An unlined canal was simulated above the irrigated area and a band of phreatophytes was simulated next to the stream. The return-flow pattern calculated for Model 118 was compared with a similar stream-aquifer system in which the deep percolation losses from the irrigated area were reduced 50 percent, the phreatophyte consumption was reduced 50 percent, a drainage ditch was constructed along the lower edge of the irrigated area and the canal losses were eliminated by lining. This comparison is shown in Figure 17. The actual values of return flow expressed in this figure are not of particular importance, but the relative position of the curves presents a good illustration of how combination water management practices may quite materially affect the surface water regime by first affecting the groundwater system. It is not the intent here to emphasize that such water management practices may be detrimental to downstream water users, but only to point out that water management or administrative personnel should be cognizant of (and be able to predict effects of) proposed water management practices.

Integrated Management of Groundwater and Surface Water

Integrated management of groundwater and surface water within a stream-aquifer system can, and often should, go well beyond the normal water management practices heretofore considered. Knowing the response behavior of a particular system, many operational procedures may be considered.

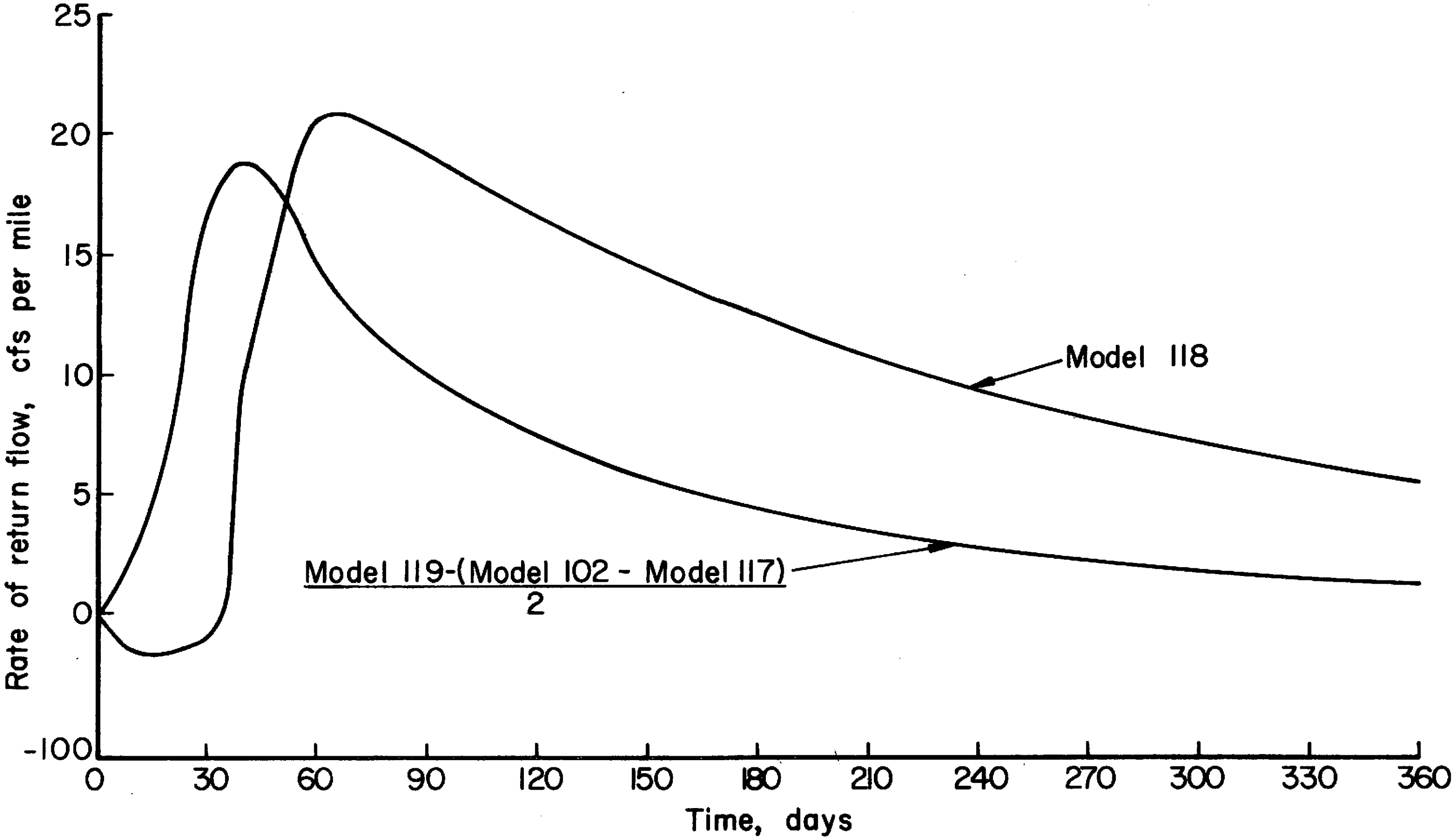


Figure 17. Composite effects of water management changes on return-flow responses.

Planned groundwater pumping programs

The groundwater reservoir within a stream-aquifer system should be considered as an active storage facility underlying the major areas of groundwater use. As in any storage facility, the normal method of operation would be to attempt to keep the reservoir as full as possible, replenishing water whenever favorable supplies are available. On the other hand withdrawals from the groundwater reservoir should be planned for utilization of water during those periods of time in which surface supplies are inadequate. In an inter-connected system withdrawal of groundwater will affect the stream flow as has been previously shown. Thus, excessive groundwater development without planned management of groundwater and surface water supplies often creates a conflict of interest between the users of water from the two sources. Under a plan of integrated management, the conflict should be alleviated. An obvious method of operation of such a system is to utilize as much of the available surface water in the upper reaches of the stream-aquifer system as possible. Thus, the major return flow is developed as high as possible in the system creating a stabilized source of supply in the lower reaches. The water users in the lower reaches of the stream-aquifer system would depend heavily upon groundwater supplies during below average surface supply years. Determining the proper balance from year-to-year for the utilization of groundwater and surface water would require setting up a specific model for the stream-aquifer system in question. General tendencies for the operational characteristics can be ascertained from the results given in this treatise, however, specific models should be constructed for each stream-aquifer system in which there will be an earnest attempt to completely integrate the two water supplies. Development of operational plans for stream-aquifer systems should include optimization studies designed to maximize predetermined objectives and minimize water loss from the system.

Planned recharge

Knowledge of the return-flow response characteristics of a stream-aquifer system can be useful in planning the timing and location of artificial recharge. For instance, it is typical that supplies of water are often more than adequate during the early spring months and become deficient during the late summer months. By utilizing the response characteristics of an aquifer, the excess water can be recharged to the groundwater system such that the water will return according to a desired pattern during the time when it is needed downstream.

Problems of implementation

The development of plans for the integrated management of groundwater and surface water in a complex stream-aquifer system will usually require a large amount of technical information and ability. Fortunately, the tools in the fields of hydraulics, hydrology, and mathematics are becoming available to handle analyses of such systems. Thus it seems likely that implementation of integrated management programs may often be deterred by social, economic and legal rather than physical problems.

The water-right, a property right prized dearly in the arid West, must be recognized and protected under any proposed change in operation. Strict compliance with this rule indicates that no changes could take place, an approach which cannot be justified as demands upon water supplies increase. The philosophy needed is that a water user is basically interested only in being able to depend upon having: (1) water of sufficient quantity, (2) water of sufficient quality, (3) delivery at times it is needed, and (4) delivery at the place of use. Thus, under an integrated management plan, a senior water-right holder would have to be assured of these four conditions to be as good or better than he has always enjoyed them, but the source may be surface water, groundwater or a mixture of the two.

SUMMARY AND CONCLUSIONS

Summary

This study was concerned with the consideration of a hydrologic unit referred to as a stream-aquifer system. As defined for this study, a stream-aquifer system is a hydrologic system in which there is an intimate hydraulic interrelationship between one or more aquifers and a perennial stream. The objectives of the study were to better understand the response behavior of typical stream-aquifer systems, to determine the response behavior in terms of water management practices, and to consider the problems and possibilities of integrated management of groundwater and surface water supplies within stream-aquifer systems.

A brief history of water development practices and policy, particularly in the Western United States, is presented. The main thrust of this presentation is that the tendency over the years has been to attempt an improvement of efficiency and availability by coordinated management of sources and uses of water within hydrologic units. This tendency is manifested by the concepts of "basin planning," "multiple purpose projects," and "comprehensive planning" which have received attention through the years.

Through the cooperation of the U.S. Geological Survey major stream-aquifer systems in the Western United States have been identified. The Soil Conservation Service provided information on the water management problems, causes, and needs found within these stream-aquifer systems. Components of stream-aquifer systems are classified into (1) input variables, (2) system parameters, and (3) output or system responses. Techniques for modeling stream-aquifer systems are discussed, and the mathematical model technique utilized is presented.

Mathematical models and digital computer solutions were utilized to simulate over 160 stream-aquifer systems. The response behavior was measured in terms of the change of groundwater levels and the pattern of outflow to the stream. The latter system response is emphasized because of the effect upon other water users which is often not considered when changes are made in water management practices. The influence of such variables and parameters as (1) the total water added to the aquifer, (2) the time distribution of the water added, (3) the areal distribution of the water added, (4) the aquifer hydraulic characteristics (such as permeability, specific yield, and saturated thickness), (5) the geometric characteristics of the aquifer, (such as converging or diverging boundaries and bedrock configuration), and (6) initial configuration of the water table surface were studied and reported herein. The effects of such water management practices as drainage, phreatophyte control, improvement of irrigation efficiency, and lining of canals were studied and discussed. Further water management practices desirable for full integrated management of groundwater and surface water within a stream-aquifer system are discussed.

Conclusions

Conclusions derived from this study include:

1. The return-flow response of stream-aquifer systems is principally dependent upon the total volume of water added to the aquifer, the width of the aquifer, and the location of the application area in respect to the stream. The effects of the time distribution of the added water and the random addition of the water to the aquifer are minor compared to the effect of the total volume of water added.

2. The effect of aquifer characteristics can be included in one aquifer constant, $\alpha = Kh/S$, where K is the permeability of the formation, h is the

saturated thickness, and S is the specific yield. Another constant, which incorporates the width of the aquifer, W, and time since water application, t, with the aquifer constant, α, to make a dimensionless term, $\alpha t/W^2$, is of importance in return-flow calculations. The percent of return flow to the stream is nearly directly proportional to the square root of this dimensionless term when it is less than 0.6.

3. Areal variations of permeability which exist within an aquifer do not greatly influence the return-flow pattern. Therefore, a single average value may be adequate to determine the return-flow response unless extremely high or low values of permeability exist along the stream.
4. A lateral boundary which converges with the stream may have a major effect upon the return-flow pattern in time and space if a sizeable downstream water table gradient exists. The configuration of the bedrock underlying the aquifer has a rather minor effect upon the return-flow response in a stream-aquifer system.
5. The initial configuration of the water table surface may be taken into consideration by adding the response from additions to (or withdrawals from) the aquifer calculated on the basis of an initially level water table. Except for thin aquifers in which the nonlinearity of the system becomes important, the use of superposition of results generally will yield only minor inaccuracies compared to those introduced by inadequate knowledge of other variables or parameters.

6. The common water management practices of drainage, phreatophyte control, improvement of irrigation practices, and lining of canals may significantly change the timing and magnitude of water available to users downstream from a stream-aquifer system.

Recommendations for Further Study

It is recommended that further study of stream-aquifer systems should include:

1. Study of the effect of auxiliary aquifers hydraulically connected to the major aquifer of the stream-aquifer system.

2. Study of the effects of less than 100 percent free intercommunication between the stream and the aquifer. This is particularly important for situations in which the water table may be drawn below the stream bed level at times, thus placing a restriction upon the hydraulic connection because of infiltration limitations of the stream bed. A recent publication by Walton (1967) covers a study made of this phenomenon.

3. Study of the quality problems and their methods of prediction for operation of stream-aquifer systems. The study reported herein has dealt entirely with the hydraulic features of stream-aquifer systems. In actual field situations, the quality of the water may place more severe restrictions upon the operational procedures than the water supply characteristics.

4. Study of how the operations of a stream-aquifer system may be planned and implemented in order to optimize particular objectives. Such a study would require the application of operations research techniques to stream-aquifer systems.

5. Study of the various legal, social, and economic problems related to the operation of stream-aquifer systems. Once an adequate model of the hydraulics of a system has been developed, one can introduce economic factors such as pumping costs, surface water delivery costs, recharge costs and income to make operational studies to maximize economic returns.

LITERATURE CITED

Banks, H.O. 1953. Utilization of underground storage reservoirs. Trans. ASCE. 118:220-234.

Bittinger, M.W., H.R. Duke and R.A. Longenbaugh. 1967. Mathematical simulation for better aquifer management. International Assoc. of Scientific Hydrol. Publ. No. 72. pp. 509-519.

Chun, R.Y.D. and E.M. Weber. 1963. Computers-tools for sound management of ground water basins. International Assoc. of Scientific Hydrol. Publ. No. 64. pp. 424-437.

Clendenen, F.B. 1954. A comprehensive plan for the conjunctive utilization of a surface reservoir with underground storage for basin-wide water supply development: Solano Project, California. D.Eng. thesis, Univ. Calif., Berkeley. 160 p.

Conkling, Harold. 1946. Utilization of ground water storage in stream system development. Trans. ASCE. 111: 275-354.

Crank, J. and P. Nicolson. 1947. A practical method for numerical evaluation of solutions of partial differential equations of the heat conduction type. Proc. Cambridge Phil. Soc. 43:50-67.

Davis, Stanley N. and Roger J.M. DeWiest. 1966. Hydrogeology. John Wiley and Sons, New York, N.Y., 463 p.

Fisk, H.N. 1944. Geological investigation of the alluvial valley of the lower Mississippi River. U.S. Army Corps of Engineers and Mississippi River Commission, Waterways Expt. Sta., Vicksburg, Miss., 78 p.

Fisk, H.N. 1947. Fine-grained alluvial deposits and their effects on Mississippi River activity. U.S. Army Corps of Engineers. Waterways Expt. Sta., Vicksburg, Miss., 82 p.

Glover, R.E. 1964. Ground-water movement. U.S. Dept. of the Interior, Bureau of Reclamation Engineering Monograph No. 31. 67 p.

Hantush, Mahdi S. 1964. Hydraulics of wells. In Advances in hydroscience, Vol. 1. Academic Press, Inc., New York. pp. 281-432.

Irby, T.L. and I.H. Arpa. 1964. Application of computer technology to reservoir studies in Canada. Paper presented at the fifteenth annual technical meeting, Petroleum and Natural Gas Division of the Canadian Institute of Mining and Metallurgy, Calgary, Alberta, Canada. 15 p.

Land, Larry F. 1967. Irrigation water supply management. Unpublished MS thesis. Colorado State University Library, Fort Collins. 78 p.

Larkin, B.K. 1964. Some stable explicit difference approximations to the diffusion equation. Math. Comp. 18(86):196-202.

Leopold, Luna B. and T. Maddock, Jr. 1953. The hydraulic geometry of stream channels and some physiographic implications. U.S. Geol. Survey Prof. Paper 252. 57 p.

Leopold, Luna B. and J. P. Miller. 1954. A postglacial chronology for some alluvial valleys in Wyoming. U.S. Geol. Survey Water Supply Paper 1261. 90 p.

Leopold, Luna B. and M.G. Wolman. 1957. River channel patterns: braided, meandering and straight. U.S. Geol. Survey Prof. Paper 282B. pp. 29-84.

Leopold, Luna B., M.G. Wolman and J.P. Miller. 1964. Fluvial processes in geomorphology. W.H. Freeman and Co. San Francisco. 522 p.

McGuinness, C.L. (1963). The role of ground water in the national water situation. U.S. Geol. Survey Water-Supply Paper 1800. 1121 p.

Maasland, D.E.L. and M.W. Bittinger (Editors). 1963. Proceedings of the symposium on transient ground water hydraulics. Colorado State University Civil Engineering Publication No. CER63DEM-MWB70. 223 p.

MacKichan, K.A. and J.C. Kammerer. 1961. Estimated use of water in the United States, 1960. U.S. Geol. Survey Circ. 456. 44 p.

Quon, D., P.M. Dranchuk, S.R. Allada, and P.K. Leung. 1965. A stable explicit computationaly efficient method for solving two-dimensional mathematical models of petroleum reservoirs. Jour. Canadian Petrol. Tech. 4:1-6.

Quon, D., P.M. Dranchuk, S.R. Allada, and P.K. Leung. 1966. Application of the alternating direction explicit procedure to two-dimensional natural gas reservoirs. Soc. of Petrol. Engrs. Jour. 40:137-142.

Peaceman, D.W. and H.H. Rachford. 1955. The numerical solution of parabolic and elliptic differential equations. Jour. Soc. Indust. Applied Math. 3:28-41.

Richtmyer, R.D. 1957. Difference methods for initial-value problems. Interscience Publ. Co. New York. 238 p.

Saul'yev, V.K. 1964. Integration of equations of parabolic type by the method of nets. The MacMillan Company, New York. 346 p.

Schumm, S.A. 1963a. Sinuosity of alluvial rivers on the Great Plains. Geol. Soc. of Amer. Bulletin. No. 74. pp. 1089-1100.

Schumm, S.A. 1963b. A tentative classification of alluvial river channels. U.S. Geol. Survey Circular 477. 10 p.

Smith, Stephen C. 1956. Problems in the use of the public district for ground water management. Land Economics 32(3):259-269.

Smith, Stephen C. 1962. The public district in the integrated management of ground and surface water: the Santa Clara County case. Giannini Foundation Res. Dept. No. 252. Univ. of Calif., Berkeley.

Spiegel, Zane. 1962. Hydraulics of certain stream-connected aquifer systems. Special Report, New Mexico State Engineer. Santa Fe, N.M. 105 p.

State of California, Department of Water Resources. 1957. The California water plan. Bulletin No. 3. Sacramento 246 p.

Strahler, Arthur N. 1960. Physical geography. 2nd ed. John Wiley and Sons, New York, N.Y. 534 p.

Thomas, H.E. 1951. The conservation of ground water. McGraw-Hill, New York, N.Y. 327 p.

Thomas, R.O. 1955. General aspects of planned groundwater utilization. Proc. ASCE. 81(sep. 706):11 p.

Thornbury, William D. 1954. Principles of geomorphology. John Wiley and Sons, Inc., New York, N.Y. 618 p.

Tyson, H.N. Jr. and Weber, E.M. 1964. Ground-water management for the nation's future--computer simulation of ground-water basins. Amer. Soc. of Civil Engr. Jour. Hydr. Div. Paper No. 3973, pp. 59-77.

U.S. Senate. 1962. Policy, standards, and procedures in the formulation, evaluation, and review of plans for use and development of water and land related resources. Senate Document 97. Washington, D.C. 13 p.

U.S. Senate Select Committee on National Water Resources. 1961. National water resources. U.S. 87th Cong., 1st sess., Senate Rept. 29, Washington, D.C. 147 p.

Varga, R.S. 1962. Matrix iterative analysis. Prentice Hall. New Jersey. 322 p.

Walton, W.C., D.L. Hills, and G.M. Grundeen. 1967. Recharge from induced streambed infiltration under varying groundwater-level and stream-stage conditions. University of Minnesota Water Resources Research Center Bulletin No. 6. 42 p.

Wiener, Aaron. 1966. The development of land and water resources in emergent economies. pp. 3-147. In General principles of water resource planning. Vol. IV, Proceedings of a Summer Institute in Water Resources, Civil Engineering Department, Utah State University, Logan,Utah. 288 p.

APPENDIXES

APPENDIX A

Table 11. Summary of USGS District Office responses to questionnaire on major stream-aquifer systems.

State	River	Reach	Selected references[a]
ARIZONA	Gila	Safford-Duncan	Gatewood et al, 1950; Thomas et al, 1963; Harshbarger et al, 1966.
	Salt	Lower Basin	" " " " "
COLORADO	Arkansas	Pueblo-State line	Weist, 1963; Voegeli & Hershey, 1965;
	So. Platte	Denver-State line	Bjorklund & Brown, 1957, Smith et al, 1964.
	Rio Grande	Del Norte-State line	Powell, 1958.
IDAHO	Snake	Bliss-Milner	Mundorff et al, 1964.
		American Falls-Roberts	" " " "
	Raft	All(?)	" " " " ; Nace, 1961, Mundorff & Siscas, 1963.
	Big Lost	All(?)	Mundorff et al, 1964; Stearns et al.
	Boise	Below Boise	" " " " ; Nace et al, 1957.
	Payette	Below Emmett	" " " " .
	Little Lost	All(?)	" " " " ; Mundorff et al, 1963.
	Big Wood	Magic Res-Hailey	Mundorff et al, 1964; Smith, 1959.
KANSAS	Republican	Colo-Nebr State lines	Prescott, 1953.
		Nebr. line-Junction City	Fishel, 1948; Frye, 1952; Fishel et al, 1956; Walters & Bayne, 1959; Bayne & Walters, 1959.
	Arkansas	Colo. line-Grt. Bend	Waite, 1942; McLaughlin, 1943, 1949; Latta, 1944, 1950; Bayne, 1956; Strammel et al, 1958.
		Grt. Bend-Okla. line	Fent, 1950; Latta, 1950; Bayne, 1956, 1960, 1962; Lane, 1960; Walters, 1961; Petri et al, 1964.
	Cimarron	Colo. line-Okla. line	McLaughlin, 1942,1946; Frye, 1942; Byrne & McLaughlin, 1947; Fader et al, 1964.
	Smoky Hill	Colo. line-Junction City	Waite, 1947; Williams & Lohman, 1949; Latta, 1949; Prescott, 1951; Johnson, 1958; Hodson, 1960, 1963,1965.
	Solomon	Above Jct. w/Smoky Hill	Frye, 1945,1949; Berry,1952; Leonard, 1952; Prescott, 1955; Bayne, 1956; Hodson, 1959, Mack, 1962.
MONTANA	Missouri	Ft. Peck Dam-St. line	Swenson, 1955.
NEBRASKA	No. Platte	All	Wenzel, et al,1946; Rapp et al, 1957; Babcock & Visher, 1951.
	So. Platte	All	Bjorklund and Brown, 1957.
	Platte	All	Lugn, 1938; Schreurs, 1956; Waite et al 1949; Keech, 1952.
	Republican	All	Bradley & Johnson, 1957; Cardwell & Jenkins, 1963; Waite et al, 1948.
NEVADA	Humboldt	Winnemucca	Cohen, 1964.
		Basin	Everett and Rush, 1965.
	Truckee	Truckee Meadows	Cohen and Loeltz, 1964.
	Walker	Smith Valley	Loeltz and Eakin, 1953.
		Mason Valley	
NORTH DAKOTA	Missouri	All	
	Yellowstone	All(?)	
	Souris	Below Verendrye	
	James	Jamestown-State line	Huxel and Petri, 1965.
	Sheyenne	Bald Hill Dam-Kathryn	Paulson, 1964; Kelley, 1966.
OKLAHOMA	Cimarron	All	Reed and others, 1953.
	No. Canadian	Above Bethany	Schoff, 1939; Schoff & Stovall, 1943; Marine & Schoff,1962; Wood & Stacy, 1965.
	Arkansas	All	Schoff & Reed, 1951; Lohman et al, 1953; Tanaka & Hollowell, 1966.
	Washita	Above Lake Texoma	Hart, 1965.
	Red	Below Lake Texoma	Barclay & Burton, 1953; Lohman et al, 1953; Davis, 1960.

Table 11. Continued.

State	River	Reach	Selected references[a]
OREGON	Willamette	Eugene-Albany	Piper, 1942.
	Willamette	Salem-Oregon City	Piper, 1942.
	Grande Ronde	LaGrande-Elgin	Hampton and Brown, 1964.
	Powder	Baker-North Powder	
	Malheur	Vale-Ontario	
	Walla Walla	Milton-Freewater-State line	Newcomb, 1965.
SOUTH DAKOTA	Big Sioux	All	Flint, 1965.
	Skunk Crk.	All(?)	" " ; Ellis & Adolphson, 1965.
	Vermillion	Lower half (?)	" " ; Lee, 1957.
	James	Lower 50 miles (?)	" " ; Simpson, 1960.
	Missouri	Below Yankton	" " ; " " .
	White	Below Interior	
	Grande	Lower 50 miles	Tychsen and Vorhis, 1955.
	Bad	Below Phillip	None.
	Cheyenne	Below Hot Springs	None.
TEXAS	Rio Grande	Above El Paso	Leggat and others, 1963.
	Comanche Springs	At Fort Stockton	Armstrong and McMillion, 1961.
	Pecos	Above Girvin	" " " " ; Ogilbee and others, 1962.
	Big Spring	At Big Spring	Livingston and Bennett,
	Los Moras Springs	At Brackettville	Petitt & George,1956; Bennett & Sayre, 1962.
	Guadalupe	Below New Braunfels	George, 1952;Petitt & George, 1956.
	San Marcos	Below San Marcos	Petitt & George, 1956; DeCook, 1963.
	Brazos	Below Whitney Dam	
	San Jacinto	Several of tributaries	Lang, Winslow & White, 1950; Wood & Gabrysch, 1965.
	Nueces	Below Lake Corpus Christi	
UTAH	Provo	Lower (Utah Valley)	Richardson, 1906; Hunt et al, 1953; Thomas et al, 1952; Cordova & Subitzky, 1965.
	Jordon	Upper (Utah Valley)	Richardson, 1906; Hunt et al, 1953; Thomas et al, 1952; Cordova & Subitzky, 1965.
	Jordon	Lower (S.L. Valley)	Richardson, 1906; Taylor & Leggette, 1949; Thomas et al, 1952; Marine & Price, 1964.
	Sevier	Upper	Carpenter and others, In press.
	"	Central	Richardson, 1907; Young & Carpenter, 1965; Bjorklund & Robinson, In press.
	"	Sevier Desert	Meinzer, 1911.
	Beaver	All (?)	Lee, 1908; Sandberg, 1966.
	Coal Creek	Cedar City Valley	Thomas & Taylor, 1946; Thomas et al, 1952; Sandberg, 1966.
	Weber & Ogden	East Shore Area	Thomas et al, 1952; Smith & Gates, 1963.
	Bear	Upper	
WASHINGTON	Spokane	Spokane Valley	Piper and LaRocque, 1944.
	Walla Walla	Above Touchet	Newcomb, 1965.
	Yakima	Main stem	Foxworthy, 1962; Kinnison & Sceva, 1963.
WYOMING	No. Platte		Weeks, 1964; Morris & Babcock, 1960; Rapp et al, 1957; Welder & Weeks,1965
	Wind		Morris and others, 1959.
	Bighorn		Robinove and Langford, 1963.
	Green River		

[a] Complete references are given on the following pages.

REFERENCES CITED IN TABLE 11

Armstrong, C. A. and L. G. McMillion. 1961 Geology and ground water resources of Pecos County, Texas. Texas Board of Water Engineers Bull. 6106. Volume I, 250 p., Volume II, 298 p.

Babcock, H. M. and F. N. Visher. 1951. Ground-water conditions in the Dutch Flats area, Scotts Bluff and Sioux Counties, Nebr. with a section on Chemical quality of the ground water by W. H. Durum. U. S. Geol. Survey Circ. 126. 51 p.

Barclay, J. E. and L. C. Burton. 1953. Ground-water resources of the terrace deposits and alluvium of western Tillman County, Oklahoma. Okla. Planning and Resources Board Bull. 12. 71 p., 6 pls., 6 figs.

Bayne, Charles K. 1956a. Geology and ground-water resources of Sheridan County, Kansas. Kansas Geol. Survey Bull. 116. 94 p.

_______1956b. Geology and ground-water resources of Reno County, Kansas. Kansas Geol. Survey Bull. 120. 130 p.

_______1960. Geology and ground-water resources of Harper County, Kansas. Kansas Geol. Survey Bull. 143. 183 p.

_______1962. Geology and ground-water resources of Cowley County, Kansas. Kansas Geol. Survey Bull. 158. 219 p.

Bayne, Charles K. and Kenneth L. Walters. 1959. Geology and ground-water resources of Cloud County, Kansas. Kansas Geol. Survey Bull. 139. 144p.

Bennett, R. R. and A. N. Sayre. 1962. Geology and ground-water resources of Kinney County, Texas. Texas Water Commission Bull. 6216. 176 p.

Berry, Delmar W. 1952. Geology and ground-water resources of Lincoln County, Kansas. Kansas Geol. Survey Bull. 95. 96 p.

Bjorklund, L. J. and R. F. Brown. 1957(1958). Geology and ground-water resources of the lower South Platte River valley between Hardin Colo. and Paxton, Nebr. with a section on Chemical quality of the ground water by H. A. Swenson. U. S. Geol. Survey Water-Supply Paper 1378. 431 p.

Bjorklund, L. J. and G. B. Robinson, Jr. In press. Ground-water resources of the Sevier River basin between Yuba Dam and Leamington Canyon, Utah. U. S. Geol. Survey Water-Supply Paper 1848.

Bradley, Edward and C. R. Johnson. 1957(1958). Geology and ground-water hydrology of the valleys of the Republican and Frenchman Rivers, Nebraska. U. S. Geol. Survey Water-Supply Paper 1360H. p. 589-713.

Byrne, Frank E. and Thad G. McLaughlin. 1947. Geology and ground-water resources of Seward County, Kansas. Kansas Geol. Survey Bull. 69. 140 p.

Cardwell, W. D. E. and E. D. Jenkins. 1963. Ground-water geology and pump irrigation in Frenchman Creek basin above Palisade, Nebr. with a section on the Chemical quality of the water by E. R. Jochens and R. A. Krieger. U. S. Geol. Survey Water-Supply Paper 1577. 472 p.

Carpenter, C. J., G. B. Robinson, Jr., and L. J. Bjorkkund. In press. Ground-water conditions and geologic reconnaissance in the upper Sevier River basin, Utah. U. S. Geol. Survey Water-Supply Paper 1836.

Cohen, Philip. 1964. Water in the Humboldt River Valley near Winnemucca, Nevada. Nevada Dept. of Conservation and Natural Resources Water Resources Bull. 27. 68 p.

Cohen, Philip and O. J. Loeltz. 1964. Evaluation of hydrogeology and hydrogeochemistry of Truckee Meadows area, Washoe County, Nev. U. S. Geol. Survey Water-Supply Paper 1779S. 63 p.

Cordova, R. M. and S. Subitzky. 1965. Ground water in northern Utah Valley, Utah: A progress report for the period 1948-63. Utah State Engineer Tech. Publ. 11. 41 p.

Davis, L. V. 1960. Geology and ground-water resources of southern McCurtain County, Oklahoma. Okla. Geol. Survey Bull. 86. 108 p., 19 figs., 1 pl.

DeCook, K. J. 1963. Geology and ground-water resources of Hays County, Tex. U. S. Geol. Survey Water-Supply Paper 1612. 72 p.

Ellis, M. J. and D. G. Adolphson. 1965. Hydrogeology of the glacial drift in the Skunk Creek-Lake Madison drainage basin, southeastern South Dakota. U. S. Geol. Survey Hydrologic Investigations Atlas 195.

Everett, D. E. and F. E. Rush. 1965. Water resources appraisal of Lovelock Valley, Pershing County, Nevada. Nevada Dept. of Cons. and Natural Resources Water Resources - Reconnaissance Series Report 32. 40 p.

Fader, Stuart W., Edwin D. Gutentag, David H. Lobmeyer and Walter R. Mayer. 1964. Geohydrology of Grant and Stanton Counties, Kansas. Kansas Geol. Survey Bull. 168. 147 p.

Fent, O. S. 1950. Geology and ground-water resources of Rice County, Kansas. Kansas Geol. Survey Bull. 85. 142 p.

Fishel, V. C. 1948. Geology and ground-water resources of Republic County and Northern Cloud County, Kansas. Kansas Geol. Survey Bull. 73. 194 p.

Fishel, V. C. and A. R. Leonard. 1956. Geology and ground-water resources of Jewell County, Kansas. Kansas Geol. Survey Bull. 115. 152 p.

Flint, R. F. 1955. Pleistocene geology of eastern South Dakota. U. S. Geol. Survey Prof. Paper 262. 173 p.

Foxworthy, B. L. 1962. Geology and ground-water resources of the Ahtanum Valley, Yakima County, Wash. U. S. Geol. Survey Water-Supply Paper 1598. 100 p.

Frye, John C. 1942. Geology and ground-water resources of Meade County, Kansas. Kansas Geol. Survey Bull. 45. 152 p.

_______1945. Geology and ground-water resources of Thomas County, Kansas. Kansas Geol. Survey Bull. 59. 111 p.

Frye, John C. and A. Byron Leonard. 1952. Pleistocene geology of Kansas. Kansas Geol. Survey Bull. 99. 230 p.

Frye, John C. and A. R. Leonard. 1949. Geology and ground-water resources of Norton County and northwestern Phillips County, Kansas. Kansas Geol. Survey Bull. 81. 144 p.

Gatewood, J. S., T. W. Robinson, B. R. Colby, J. D. Hem and L. C. Halpenny. 1950. Use of water by bottom-land vegetation in lower Safford Valley, Arizona. U. S. Geol. Survey Water-Supply Paper 1103. 210 p.

George, W. O. 1952(1953). Geology and ground-water resources of Comal County, Texas, with sections on surface-water supplies, by S. D. Breeding, and chemical character of the water, by W. W. Hastings. U. S. Geol. Survey Water-Supply Paper 1138. 126 p.

Hampton, E. R. and S. G. Brown. 1964. Geology and ground-water resources of the upper Grande Ronde River basin, Union County, Oregon. U. S. Geol. Survey Water-Supply Paper 1597. 99 p.

Harshbarger, J. W., D. D. Lewis, H. E. Skibitzke, W. L. Heckler and L. R. Kister. 1966. Arizona water. U. S. Geol. Survey Water-Supply Paper 1648. 85 p.

Hart, D. L., Jr. 1965. Ground-water levels in the alluvial deposits of the Washita River between Clinton and Anadarko, Oklahoma. Okla. Water Resources Board Bull. 26. 23 p., 12 figs.

Hodson, Warren G. 1959. Geology and ground-water resources of Mitchell County, Kansas. Kansas Geol. Survey Bull. 140. 132 p.

_______1963. Geology and ground-water resources of Wallace County, Kansas. Kansas Geol. Survey Bull. 161. 180 p.

_______1965. Geology and ground-water resources of Trego County, Kansas. Kansas Geol. Survey Bull. 174. 80 p.

Hodson, Warren G. and Kenneth D. Wahl. 1960. Geology and ground-water resources of Gove County, Kansas. Kansas Geol. Survey Bull. 145. 126 p.

Hunt, C. B., H. D. Varnes and H. E. Thomas. 1953. Geology of northern Utah Valley, Utah. U. S. Geol. Survey Prof. Paper 257. p. 1-99.

Huxel, C. J., Jr., and L. R. Petri. 1965. Geology and ground-water resources of Stutsman County, North Dakota. North Dakota State County Commission County Ground Water Studies 1. Bull. 41.

Johnson, Carlton R. 1958. Geology and ground-water resources of Logan County, Kansas. Kansas Geol. Survey Bull. 129. 177 p.

Keech, C. F. 1952. Ground-water resources of the Wood River unit of the lower Platte River basin, Nebraska. U. S. Geol. Survey Circ. 139. 96 p.

Kelly, T. E. 1966. Geology and ground-water resources of Barnes County, North Dakota. North Dakota State County Commission County Ground Water Studies 4. Bull. 43.

Kinnison, H. B. and J. E. Sceva. 1963. Effects of hydraulic and geologic factors on streamflow of the Yakima River basin, Washington. U. S. Geol. Survey Water-Supply Paper 1595. 134 p.

Lane, Charles W. 1960. Geology and ground-water resources of Kingman County, Kansas. Kansas Geol. Survey Bull. 144. 173 p.

Lang, J. W., A. G. Winslow and W. N. White. 1950. Geology and ground-water resources of the Houston District, Texas. Texas Board Water Engineers Bull. 5001. 59 p.

Latta, Bruce F. 1944. Geology and ground-water resources of Finney and Gray Counties, Kansas. Kansas Geol. Survey Bull. 55. 272 p.

_______1949. Ground-water conditions in the Smoky Hill Valley in Saline, Dickinson and Geary Counties Kansas. Kansas Geol. Survey Bull. 84. 152 p.

_______1950. Geology and ground-water resources of Barton and Stafford Counties, Kansas. Kansas Geol. Survey Bull. 88. 228 p.

Lee, K. Y. 1957. Geology and shallow water resources between Hoven and Bowdle, South Dakota. South Dakota Geol. Survey Report of Investigation. No. 82. 59 p.

Lee, W. T. 1908. Water resources of Beaver Valley, Utah. U. S. Geol. Survey Water-Supply Paper 217. 57 p.

Leggat, E. R., M. E. Lowry and J. W. Hood. 1963. Ground water resources of the lower Mesilla Valley, Texas and New Mexico. U. S. Geol. Survey Water-Supply Paper 1669AA. p. AA1-AA49.

Leonard, Alvin R. 1952. Geology and ground-water resources of the North Fork Solomon River in Mitchell, Osborne, Smith and Phillips Counties, Kansas. Kansas Geol. Survey Bull. 98. 124 p.

Livingston, Penn and R. R. Bennett. 1944. Geology and ground water resources of the Big Spring area, Texas. U. S. Geol. Survey Water-Supply Paper 913. 114 p.

Loeltz, O. J. and T. E. Eakin. 1953(1954). Geology and water resources of Smith Valley, Lyon and Douglas Counties, Nev. U. S. Geol. Survey Water-Supply Paper 1228. 89 p.

Lohman, S. W., V. M. Burtis, et al. 1953. General availability of ground water and depth to water level in the Arkansas, White and Red River basins. U. S. Geol. Survey Hydrologic Investigations Atlas HA-3.

Lugn, A. L. and L. K. Wenzel. 1938. Geology and ground-water resources of south-central Nebraska, with special reference to the Platte River Valley between Chapman and Gothenburg. U. S. Geol. Survey Water-Supply Paper 779. 242 p.

McLaughlin, Thad G. 1942. Geology and ground-water resources of Morton County, Kansas. Kansas Geol. Survey Bull. 40. 126 p.

_______1943. Geology and ground-water resources of Hamilton and Kearny Counties, Kansas. Kansas Geol. Survey Bull. 49. 220 p.

_______1946. Geology and ground-water resources of Grant, Haskell and Stevens County, Kansas. Kansas Geol. Survey Bull. 61. 221 p.

_______1949. Geology and ground-water resources of Pawnee and Edwards Counties, Kansas. Kansas Geol. Survey Bull. 80. 189 p.

Mack, Leslie E. 1962. Geology and ground-water resources of Ottawa County, Kansas. Kansas Geol. Survey Bull. 154. 145 p.

Marine, I. W. and Don Price. 1964. Geology and ground-water resources of the Jordon Valley, Utah. Utah Geol. and Minerological Survey Water Resources Bull. 7. 68 p.

Marine, I. W. and S. L. Schoff. 1962. Ground-water resources of Beaver County, Oklahoma. Okla. Geol. Survey Bull. 97. 74 p., 2 pls., 12 figs.

Meinzer, O. E. 1911. Ground water in Juab, Millard and Iron Counties, Utah. U. S. Geol. Survey Water-Supply Paper 277. 162 p.

Morris, D. A. and H. M. Babcock. 1960(1961). Geology and ground-water resources of Platte County, Wyo. with a section on Chemical quality of the water by R. H. Langford. U. S. Geol. Survey Water-Supply Paper 1490. 195 p.

Morris, D. A., O. M. Hackett, K. E., Vanlier and E. A. Moulder. 1959. Ground-water resources of the Riverton irrigation project area, Wyoming with a section on Chemical quality of ground water by W. H. Durum. U. S. Geol. Survey Water-Supply Paper 1375. 205 p.

Mundorff, M. J., H. C. Broom and Chabot Kilburn. 1963. Reconnaissance of the hydrology of the Little Lost River basin, Idaho. U. S. Geol. Survey Water-Supply Paper 1539Q. p. Q1-Q51.

Mundorff, M. J., E. G. Crosthwaite and Chabot Kilburn. 1964. Ground water for irrigation in the Snake River basin in Idaho. U. S. Geol. Survey Water-Supply Paper 1654. 224 p.

Mundorff, M. J. and H. G. Siscos. 1963. Ground water in the Raft River basin, Idaho, with special reference to irrigation use, 1956-60. U. S. Geol. Survey Water-Supply Paper 1619CC. p. CC1-CC23

Nace, R. L. 1961. Water resources of the Raft River basin, Idaho-Utah. U. S. Geol. Survey Water-Supply Paper 1587. 138 p.

Nace, R. L., S. W. West and R. W. Mower. 1957. Feasibility of ground-water features of the alternate plan for the Mountain Home project, Idaho. U. S. Geol. Survey Water-Supply Paper 1376. 121 p.

Newcomb, R. C. 1965. Geology and ground-water resources of the Walla Walla River basin, Washington-Oregon. Washington Div. of Water Resources Water-Supply Bull. 21. 151 p.

Ogilbee, William, J. B. Wesselman and Burdge Irelan. 1962. Geology and ground water resources of Reeves County, Texas. Texas Board of Water Engineers Bull. 6214. Volume I, 213 p., Volume II, 248 p.

Paulson, Q. F. 1964. Geologic factors affecting discharge of the Sheyenne River in southeastern North Dakota. U. S. Geol. Survey Prof. Paper 501-D, p. D177-D181.

Petitt, B. M., Jr., and W. O. George. 1956. Ground-water resources of the San Antonio area, Texas. Texas Board Water Engineers Bull. 5608. Volume I, 85 p., Volume II, Part I, 255 p., Volume II, Part II, 288 p., Volume II, Part III, 231 p.

Petri, L. R., C. W. Lane and L. W. Furness. 1964. Water resources of the Wichita area, Kansas. U. S. Geol. Survey Water-Supply Paper 1499-I. p. 11-169.

Piper, A. M. 1942. Ground-water resources of the Willamette Valley, Oregon. U. S. Geol. Survey Water-Supply Paper 890. 194 p.

Piper, A. M. and G. A. La Rocque, Jr. 1944. Water-table fluctuations in the Spokane Valley and contiguous area, Washington-Idaho. U. S. Geol. Survey Water-Supply Paper 889B. p. 83-139.

Powell, W. J. 1958. Ground-water resources of the San Luis Valley, Colo. with a section on an inflow-outflow study of the area by P. B. Mutz. U. S. Geol. Survey Water-Supply Paper 1379. 284 p.

Prescott, Glenn C., Jr. 1951. Geology and ground-water resources of Lane County, Kansas. Kansas Geol. Survey Bull. 93. 126 p.

_______1953. Geology and ground-water resources of Cheyenne County, Kansas. Kansas Geol. Survey Bull. 100. 106 p.

_______1955. Geology and ground-water resources of Graham County, Kansas. Kansas Geol. Survey Bull. 110. 98 p.

Rapp, J. R., F. M. Visher and R. T. Littleton. 1957. Geology and ground-water resources of Goshen County, Wyo. with a section on Chemical quality of the ground water by W. H. Durum. U. S. Geol. Survey Water-Supply Paper 1377. 145 p.

Reed, W. E., J. E. Barclay, J. L. Mogg and G. H. Peden. 1953. Ground-water resources of terrace deposits along the northeast side of the Cimarron River in Alfalfa, Garfield, Kingfisher and Major Counties, Oklahoma. Okla. Planning and Resources Board Bull. 9. 101 p., 9 pls., 5 figs.

Richardson, G. B. 1906. Underground water in the valleys of Utah Lake and Jordon River, Utah. U. S. Geol. Survey Water-Supply Paper 157. 81 p.

_______1907. Underground water in Sanpete and central Sevier Valleys, Utah. U. S. Geol. Survey Water-Supply Paper 199. 63 p.

Robinove, C. J. and R. H. Langford. 1963. Geology and ground-water resources of the Greybull River-Dry Creek area, Wyoming. U. S. Geol. Survey Water-Supply Paper 1596. 88 p.

Sandberg, G. W. 1966. Ground water resources of selected basins in southwestern Utah. Utah State Engineer Tech. Publ. 13. 46 p.

Schoff, S. L. 1939. Geology and ground-water resources of Texas County, Oklahoma. Okla. Geol. Survey Bull. 59. 248 p., 5 pls., 13 figs.

Schoff, S. L. and E. W. Reed. 1951 Ground-water resources of the Arkansas River flood plain near Fort Gibson, Muskogee County, Oklahoma. Okla. Geol. Survey Circ. 28. 55 p., 12 pls., 1 fig.

Schoff, S. L. and J. W. Stovall. 1943. Geology and ground-water resources of Cimarron County, with a section on Mesozoic stratigraphy. Okla. Geol. Survey Bull. 64. 317 p., 24 pls., 27 figs.

Schreurs, R. L. 1956. Geology and ground-water resources of Buffalo County and adjacent area, Nebraska with a section on Chemical quality of the ground water by F. H. Rainwater., U. S. Geol. Survey Water-Supply Paper 1358. 175 p.

Simpson, H. E. 1960. Geology of the Yankton area, South Dakota and Nebraska. U. S. Geol. Survey Professional Paper 328. 124 p.

Smith, R. E. and J. S. Gates. 1963. Ground-water conditions in the southern and central parts of the east shore area, Utah, 1953-61. Utah Geol. and Minerological Survey Water-Resources Bull. 2. 48 p.

Smith, R. O. 1959. Ground-water resources of the middle Big Wood River-Silver Creek area, Blaine County, Idaho. U. S. Geol. Survey Water-Supply Paper 1478. 64 p.

Smith, R. O., P. A. Schneider, Jr., and L. R. Petri. 1964. Ground-water resources of the South Platte River basin in western Adams and southwestern Weld Counties, Colo. U. S. Geol. Survey Water-Supply Paper 1658. 132 p.

Stearns, H. T., Lynn Crandall and W. G. Steward. 1938(1939). Geology and ground-water resources of the Snake River Plain in southeastern Idaho. U. S. Geol. Survey Water-Supply Paper 774. 268 p.

Stramel, G. J., Charles W. Lane and Warren G. Hodson. 1958. Geology and ground-water hydrology of the Ingalls Area, Kansas. Kansas Geol. Survey Bull. 132. 154 p.

Swenson, F. A. 1955(1956). Geology and ground-water resources of the Missouri River valley in northeastern Montana. U. S. Geol. Survey Water-Supply Paper 1263. 128 p.

Tanaka, H. H. and J. R. Hollowell. 1966. Hydrology of the alluvium of the Arkansas River, Muskogee, Oklahoma, to Fort Smith, Arkansas. U. S. Geol. Survey Water-Supply Paper 1809-T, 42 p., 3 pls., 6 figs.

Taylor, G. H. and R. M. Leggette. 1949. Ground water in the Jordon Valley, Utah. U. S. Geol. Survey Water-Supply Paper 1029. 357 p.

Thomas, H. E., et al. 1963. Effects of drought in the Colorado River basin. U. S. Geol. Prof. Paper 372F. p. F1-F51.

Thomas, H. E., W. B. Nelson, B. E. Lofgren and R. G. Butler. 1952. Status of development of selected ground-water basins in Utah. Utah State Engineer Tech. Publ. 7. 96 p.

Thomas, H. E. and G. H. Taylor. 1946(1947). Geology and ground-water resources of Cedar City and Parowan Valleys, Iron County, Utah. U. S. Geol. Survey Water-Supply Paper 993. 210 p.

Tychsen, P. C. and R. C. Vorhis. 1955. Reconnaissance of geology and ground water in the lower Grand River valley, South Dakota with a section on Chemical quality of the ground water by E. R. Jochens. U. S. Geol. Survey Water-Supply Paper 1298. 33 p.

Voegeli, P. T., Sr., and L. A. Hershey. 1965. Geology and ground-water resources of Prowers County, Colo. U. S. Geol. Survey Water-Supply Paper 1772. 101 p.

Waite, H. A., et al. 1948. Progress report on the ground-water hydrology of the Republican and Frenchman River valleys (Nebr.) with a section on the chemical quality of the ground water by H. A. Swenson. U. S. Geol. Survey Circ. 19. 83 p.

_______1949. Preogress report on the geology and ground-water hydrology of the lower Platte River valley, Nebr. with a section on the chemical quality of the ground water by H. A. Swenson. U. S. Geol. Circ. 20. 211 p.

Waite, Herbert A. 1942. Geology and ground-water resources of Ford County, Kansas. Kansas Geol. Survey Bull. 43. 250 p.

_______1947. Geology and ground-water resources of Scott County, Kansas. Kansas Geol. Survey Bull. 66. 216 p.

Walters, Kenneth L. 1961 Geology and ground-water resources of Sumner County, Kansas. Kansas Geol. Survey Bull. 151. 198 p.

Walters, Kenneth L. and Charles K. Bayne. 1959. Geology and ground-water resources of Clay County, Kansas. Kansas Geol. Survey Bull. 136. 106 p.

Weeks, E. P. 1964. Hydrologic conditions in the Wheatland Flats area, Platte County, Wyo. U. S. Geol. Survey Water-Supply Paper 1783. 79 p.

Weist, W. G., Jr. 1963. Water in the Dakota and Purgatoire Formations in Otero County and the southern part of Crowley County, Colo. U. S. Geol. Survey Water-Supply Paper 1669P. p. P1-P17.

Welder, G. E. and E. P. Weeks. 1965. Hydrologic conditions near Glendo, Platte County, Wyo. U. S. Geol. Survey Water-Supply Paper 1791. 82 p.

Wenzel, L. K., R. C. Cady and H. A. Waite. 1946. Geology and ground-water resources of Scotts Bluff County, Nebraska. U. S. Geol. Survey Water-Supply Paper 943. 150 p.

Williams, Charles C. and Stanley W. Lohman. 1949. Geology and ground-water resources of a part of south-central Kansas with special reference to the Wichita Municipal Water Supply. Kansas Geol. Survey Bull. 79. 455 p.

Wood, L. A. and R. K. Gabrysch. 1965. Analog model study of ground-water in the Houston District, Texas. (Contains a section on design, construction and use of electric analog models, by E. P. Patton, Jr.). Texas Water Commission Bull. 6508. 103 p.

Wood, P. R. and B. L. Stacy. 1965. Geology and ground-water resources of Woodward County, Oklahoma. Okla. Water Resources Board Bull. 21. 114 p., 7 pls., 6 figs.

Young, R. A. and C. H. Carpenter. 1965. Ground-water conditions and storage in the central Sevier Valley, Utah. U. S. Geol. Survey Water-Supply Paper 1787. 95 p.

APPENDIX B

Table 12. Summary of SCS evaluations of water management problems, causes and needs within major stream-aquifer systems of the Western States.

Water management(a)

River	Reach	Problems								Causes								Needs							
		1	2	3 a	3 b	4 a	4 b	4 c	5	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Arizona																									
Gila	Safford-Duncan Valleys	/	X	/	X	X		/		/		/						/		X	X		/		
Salt	Lower Basin		/			/		/		/		/								X	X		/		
California																									
Sacramento	Red Bluff-Walnut Grove	X	/		/					/		/	/		/	/		X	/	/	/	/	X		
Trinity	Coffee Crk-Minersville								/																/
Feather	Marysville-Jct w/Sacr. River	X	/		/					/		/	/					X	/	/	/		X		
American	Folsom-Sacramento River	/				/												/							
Colorado	Parker-Palo Verde	X	X			X			X	/		X	/					X	X	X	/	/	X	/	
"	Imperial Res-Gulf of Calif.	X	X			X			X	/		X						X	X	X	/	/	X	/	
Colorado																									
Arkansas	Pueblo-State Line	/		X		/		/		/	/	/	/			X		/	/	X	/	X		X	
So. Platte	Denver-State Line	/	/	/		/	/			/	/	X	/			X		/		X	/	X		X	
Rio Grande	Del Norte-State Line	X	/		/	/				X	/	X	X		/	X		X		X	X	/		X	
Idaho																									
Snake	Bliss-Milner						/	/		/		/								/	/	X	/		
"	Amer. Falls-Roberts	/	/				/	/	X	/		X	/	/		/	X	X		X	/	X	/		X
Raft	All	/		/	X	/				/		/				/				/	/	X	X		
Big Lost	All	/	/	/	X				/	X	X	X		/		X	/		/	X	X	X	X		/
Boise	Below Boise	X	/				/	/		/	/	X	/	/	/	X		/		X	/	X	/	/	
Payette	Below Emmett	X	/						X	/		X	/	X	/	X	X	X		X	/	X	/		X
Little Lost	All		/	/	X				X	X		/				X	/			/	X	/	/		/
Big Wood	Magic Res-Hailey	X	/	/	X				X	X		X				X	X			X	X	X	X		X
Kansas																									
Republican	Colo. St. Line-Nebr. St. Line														/			/	/					/	
"	Nebr. St. Line-Junction City	/	/			/				/	/				/			/	/	/	/			/	
Arkansas	Colo. St. Line-Great Bend		/		/	/						/			/	/		/	/	/		/		/	
"	Great Bend-Okla. St. Line		/												/			/	/					/	
Cimarron	Colo. St. Line-Okla. St. Line		/																/					/	
Smoky Hill	Colo. St. Line-Junction City		/			X								/		/			/			/		/	
Solomon	Above Jct. with Smoky Hill	/	/			/				/	/	/		/	/	/		/	/		/	/		/	
Montana																									
Missouri	Ft. Peck-State Line	/				X						/			X			/		X			X		
Nebraska																									
North Platte	All	X	/			X	X			X	X	X	X		/	/		X	/	X	X		/	/	
South Platte	All	/	/			X	X			/		X						/	/	X		X	/	/	
Platte	All	X	/	/	X	/	X			/	/	X	/		X	X		X	/	X	/	X	/	/	
Republican	All	X	X			/	X			X	X	/	X					X	/	X	/	X		/	

Table 12 (Continued)

										Water management(a)															
River	Reach	Problems								Causes								Needs							
				3		4																			
		1	2	a	b	a	b	c	5	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Nevada																									
Humbolt	Winnemucca																								
"	Basin																								
Truckee	Truckee Meadows																								
Walker	Smith Valley																								
"	Mason Valley																								
New Mexico																									
Gila	Red Rock-Ariz. St. Line		X					/		/		X							X	X	X				
Rio Grande	Colo. St. Line-So. 6 miles																								
" "	Pilar-Nr. Totavi	X	X							X		X			X			X	X	X	X		/		
" "	Cochiti-Bernardo	X	X			/	/	X		X					X			X	X	X	X				
" "	Jct. of Rio Salado-Nr. Hatch	X	X		X	X		X		X		/			/			X	X	X	X	/	/		
" "	Nr. Radium Springs-El Paso		/		/	/		X		/		/			/	/			/	/	/				
No. Dakota																									
Missouri	All	/													/			/							
Yellowstone	All	/						/		/					/			/		/					
Souris	Below Verendrye		X									X								X			X		
James	Jamestown-State Line	/	/												/			/							
Sheyenne	Balo Hill Dam-Kathryn																								
Oklahoma																									
Cimarron	All					X											X								X
No. Canadian	Above Bethany	X							X		X				X			X							
Arkansas	All	X				X									X		X	X							X
Washita	Above Lake Texoma	/	/							/					/			/							
Red	Below Lake Texoma	X													X			X							
Oregon																									
Willamette	Eugene-Albany	X													X			X							
"	Salem-Oregon City	X				X									X			X							
Grande Ronde	La Grande-Elgin	X			X					X		X								X	X		X		
Powder	Baker-North Powder	X			X	X				X		X				X				X	X	X	X		
Malheur	Vale-Ontario	X			X					X		X	X							X	X		X		
Walla Walla	Milton-Freewater-St. Line	X										X			X					X			X		
So. Dakota																									
Big Sioux	All	X	/												X	/		X				/			
Skunk Creek	All	/													/	/						/			
Vermillion	Lower Half	/	/		/										/	/						/			
James	Lower 50 miles				/			/							/	/						/			
Missouri	Below Yankton	X			/							/	/		X	/		X				/			
White	Below Interior				/	/									/	/		/				/			
Grande	Lower 50 miles				/	/									/	/						/			
Bad	Below Phillip				/	/							/			/						/			
Cheyenne	Below Hot Springs				/	/						/	/			/				/		/			

Table 12.(Continued).

River	Reach	Problems								Water management(a) Causes								Needs							
				3		4																			
		1	2	a	b	a	b	c	5	1	2	3	4	5	6	7	8	1	2	3	4	5	6	7	8
Texas																									
Rio Grande	Above El Paso	/	X		X													/	X						
Comanche Sprgs.	At Fort Stockton	/	/	X								/	X					/	X	/		X			
Pecos	Above Girvin	/	X			X				/		X						/	/	X	/				
Big Spring	At Big Spring			X												X						X			
Los Moras Sprgs.	At Brackettville		X														X								X
Guadalupe	Below New Braunfels		X														X								X
San Marcos	Below San Marcos		X														X								X
Brazos	Below Whitney Dam	/	/	/												/		/	/	/		/			
San Jacinto	Several of Tributaries	/													X			/							
Nueces	Below Lake Corpus Christi	/	/	/									/			/		/	X			/			
Utah																									
Provo	Lower (Utah Valley)	X										X	X	/	/			X		X	/		/		
Jordon	Utah Valley																								
"	Lower (Salt Lake Valley)	X				X	X	/		/		X	X		X	/		X		X	X		/		
Sevier	Upper		X	X	X							/	/						/	X			X	X	
"	Central	X	X	X	X	/				/			/	X	/			X	/	X			X	X	
"	Sevier Desert			X		X									/	X						X	/	X	
Beaver	All	X		X						X		X				/		X		X	X	/	/		
Coal Creek	Cedar City Valley		/	X	X			/		/		X	/			/			/	X	X	/	/	X	
Weber & Ogden	East Shore Area	X	X	X						/		X	X	X	X	X		X	X	/	X	/		X	
Bear	Upper		X									X								X			/		
Washington																									
Spokane	Spokane Valley				X	X	X						X			X						X	X		
Walla Walla	Above Touchet				X							X	X			X						X	X		
Yakima	Main stem	X		X	X	X				X	X	X	X			X				X	X	X	X		
Wyoming																									
No. Platte	All	X								X		X	X					X		X	X		/		
Wind	All	X								X		X	X					X		X	X		/		
Bighorn	All	X								X		X	X					X		X	X		/		
Green River	All		/							X		X						/	/	X	X		/		

(a) The numbers in the table are keyed to the items below. Marks in the squares indicate the following:

X - The item is a major problem, cause, or need;
/ - The item is a minor problem, cause, or need;
blank - The item is of little or no importance.

(continued)

Table 12 (Continued)

Water management problems	Causes	Needs
1. Drainage problems.	1. Canal seepage.	1. Artificial drainage.
2. Non-beneficial water use (phreatophytes, evaporation from high water table, etc.).	2. Reservoir seepage.	2. Phreatophyte control.
3. Conflicts between surface water and ground water users: (a) now a problem (b) potentially a problem.	3. Excessive irrigation applications.	3. Improvement of field irrigation.
4. Quality problems (a) Chemical (b) Bacteriological (c) Physical (Color, odor, taste, etc.).	4. Water use on adjoining uplands.	4. Lining or sealing canals and/or reservoirs.
5. Other.	5. Leakage from underlying artesian aquifers.	5. Planned coordinated or integrated management of interrelated groundwater and surface water.
	6. Poor natural drainage (low transmissibility).	6. More information on system responses to changes in management practices.
	7. Lack of coordinated development and use of interrelated groundwater and surface water.	7. Legislation allowing coordinated or integrated management of interrelated groundwater and surface.
	8. Other.	8. Other.

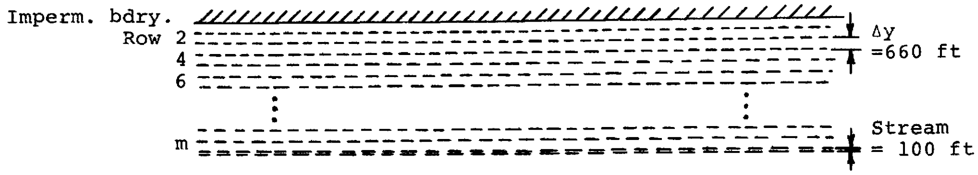
APPENDIX C

Table 13. Description of one-dimensional models analyzed^{a}.

Model no.	No. of active 660' rows	Perme-ability pattern^{b}	Specific yield pattern^{c}	Initial water table^{d}	Bed-rock^{e}	Land sur-face^{f}	Canal po-sition^{g}	Irr. area po-sition^{h}	With-drawal area position^{i}	Canal Q^{j}	Irr. area Q^{k}	With drawal Q (Neg)^{l}
101	16	1	1	1	1	1	0	1-16	0	0	1	0
102	16	1	1	1	1	1	0	1-12	0	0	1	0
103	16	1	1	1	1	1	0	1-8	0	0	1	0
104	16	1	1	1	1	1	0	1-4	0	0	1	0
105	16	1	1	1	1	1	0	5-16	0	0	1	0
106	16	1	1	1	1	1	0	5-12	0	0	1	0
107	16	1	1	1	1	1	0	5-8	0	0	1	0
108	16	1	1	1	1	1	0	9-16	0	0	1	0
109	16	1	1	1	1	1	0	9-12	0	0	1	0
110	16	1	1	1	1	1	0-1	0	0	1	0	0
111	16	1	1	1	1	1	4-5	0	0	1	0	0
112	16	1	1	1	1	1	8-9	0	0	1	0	0
113	16	1	1	1	1	1	12-13	0	0	1	0	0
114	16	1	1	1	1	1	0-1	1-16	0	1	1	0
115	16	1	1	1	1	1	4-5	5-16	0	1	1	0
116	16	1	1	1	1	1	8-9	9-16	0	1	1	0
117	16	1	1	1	1	1	0	1-12	16	0	1	1
118	16	1	1	1	1	1	0-1	1-12	16	1	1	1
119	12	1	1	1	1	1	0	1-12	0	0	1	0
120	12	1	1	1	1	1	0	1-8	0	0	1	0
121	12	1	1	1	1	1	0	1-4	0	0	1	0
122	12	1	1	1	1	1	0	5-12	0	0	1	0
123	12	1	1	1	1	1	0	1-8	0	0	1	0
124	12	1	1	1	1	1	0	9-12	0	0	1	0
125	16	2	1	1	1	1	0	1-16	0	0	1	0
126	16	3	1	1	1	1	0	1-16	0	0	1	0
127	16	4	1	1	1	1	0	1-16	0	0	1	0
128	16	5	1	1	1	1	0	1-16	0	0	1	0
129	16	2	1	1	1	1	0	1-8	0	0	1	0
130	16	3	1	1	1	1	0	1-8	0	0	1	0
131	16	4	1	1	1	1	0	1-8	0	0	1	0
132	16	5	1	1	1	1	0	1-8	0	0	1	0
133	16	2	1	1	1	1	0-1	0	0	1	0	0
134	16	3	1	1	1	1	0-1	0	0	1	0	0
135	16	4	1	1	1	1	0-1	0	0	1	0	0
136	16	5	1	1	1	1	0-1	0	0	1	0	0
137	16	4	2	1	1	1	0	1-16	0	0	1	0
138	16	3	1	1	2	1	0	1-16	0	0	1	0
139	16	4	1	1	3	1	0	1-16	0	0	1	0
140												
141	16	6	1	1	1	1	0	1-16	0	0	1	0
142	16	7	1	1	1	1	0	1-16	0	0	1	0
143	16	8	1	1	1	1	0	1-16	0	0	1	0
144	16	9	1	1	1	1	0	1-16	0	0	1	0
145												
146	16	1	1	1	4	1	0	1-16	0	0	1	0
147	16	1	1	1	5	1	0	1-16	0	0	1	0
148	16	1	1	1	6	1	0	1-16	0	0	1	0
151	16	1	1	1	1	1	0	1-16	0	0	2	0
152	16	1	1	1	1	1	0	1-16	0	0	3	0
153	16	1	1	1	1	1	0	1-16	0	0	4	0
154	16	1	1	1	1	1	0	1-16	0	0	5	0
155	16	1	1	1	1	1	0	1-16	0	0	6	0
158	4	1	1	1	1	1	0	1-4	0	0	1	0
159	8	1	1	1	1	1	0	1-8	0	0	1	0
160	20	1	1	1	1	1	0	1-20	0	0	1	0
161	24	1	1	1	1	1	0	1-24	0	0	1	0
162	32	1	1	1	1	1	0	1-32	0	0	1	0
163	40	1	1	1	1	1	0	1-40	0	0	1	0

Footnotes. Appendix C

[a]Basic arrangement for one-dimensional Models



[b]Permeability

	Pattern no.								
	1	2	3	4	5	6	7	8	9
Row no. 1	0.01	0.001	0.005	0.02	0.05	0.006	0.002	0.006	0.001
2	0.01	0.001	0.005	0.02	0.05	0.006	0.002	0.006	0.001
3	0.01	0.001	0.005	0.02	0.05	0.007	0.004	0.008	0.006
4	0.01	0.001	0.005	0.02	0.05	0.007	0.004	0.008	0.006
5	0.01	0.001	0.005	0.02	0.05	0.008	0.006	0.010	0.011
6	0.01	0.001	0.005	0.02	0.05	0.008	0.006	0.010	0.011
7	0.01	0.001	0.005	0.02	0.05	0.009	0.008	0.013	0.016
8	0.01	0.001	0.005	0.02	0.05	0.009	0.008	0.013	0.016
9	0.01	0.001	0.005	0.02	0.05	0.010	0.010	0.016	0.022
10	0.01	0.001	0.005	0.02	0.05	0.010	0.010	0.016	0.022
11	0.01	0.001	0.005	0.02	0.05	0.011	0.012	0.013	0.016
12	0.01	0.001	0.005	0.02	0.05	0.011	0.012	0.013	0.016
13	0.01	0.001	0.005	0.02	0.05	0.012	0.014	0.010	0.011
14	0.01	0.001	0.005	0.02	0.05	0.012	0.014	0.010	0.011
15	0.01	0.001	0.005	0.02	0.05	0.013	0.016	0.008	0.006
16	0.01	0.001	0.005	0.02	0.05	0.013	0.016	0.008	0.006
17	0.01	0.001	0.005	0.02	0.05	0.014	0.018	0.006	0.001

[c]Specific yield

Pattern No. 1--Uniform throughout model at 0.20.
Pattern No. 2--Uniform throughout model at 0.40.

[d]Initial water table

Condition No. 1--Level.

[e]Bedrock configuration

Condition No. 1--Level, 50 feet below initial water table elevation.
Condition No. 2--Level, 100 feet below initial water table elevation.
Condition No. 3--Level, 25 feet below initial water table elevation.
Condition No. 4--Sloping toward river at 8 feet per mile. Average bedrock elevation 50 feet below initial water table elevation.
Condition No. 5--Sloping away from river at 8 feet per mile. Average bedrock elevation 50 feet below initial water table elevation.
Condition No. 6--Sloping away from river and impermeable boundary at 16 feet per mile to low point at center of model. Average bedrock elevation 50 feet below initial water table elevation.

[f]Land surface

Condition No. 1--Level, 10 feet above initial water table elevation.

[g]Canal position (Canal 50 feet in width)

0 --indicates no canal.
0-1 --indicates canal is located between the impermeable boundary and the first 660-foot row
4-5 --indicates canal is located between the 4th and 5th 660-foot rows.
ETC.

[h]Irrigated area position

1-16--indicates water applied to 660-foot rows 1 through 12, with remaining rows in the model not receiving water.
ETC.

[i]Withdrawal area position (660-feet wide)

0 --indicates no withdrawal of water.
16 --indicates row No. 16 has water withdrawn from it.

(continued)

Footnotes Appendix C

[j] Canal input Q
0 indicates no leakage from canal to groundwater system.
1 indicates canal leakage to groundwater at the rate of 2 acre-feet per day per mile of canal length over the time period t=0 to t=50 days.

[k] Irrigated area input Q
0 indicates no water percolation from irrigated lands to the groundwater system.
1 indicates deep percolation from irrigated lands to the groundwater as follows:

0.1 ft during t = 0 to 10 days
0.2 ft during t = 10 to 20 days
0.4 ft during t = 20 to 30 days
0.2 ft during t = 30 to 40 days
0.1 ft during t = 40 to 50 days
and no deep percolation after t = 50 days.

2 indicates deep percolation as follows:

0.05 ft during t = 0 to 10 days
0.1 ft during t = 10 to 20 days
0.2 ft during t = 20 to 30 days
0.1 ft during t = 30 to 40 days
0.05 ft during t = 40 to 50 days

3 indicates deep percolation as follows:

0.2 ft during t = 0 to 10 days
0.4 ft during t = 10 to 20 days
0.8 ft during t = 20 to 30 days
0.4 ft during t = 30 to 40 days
0.2 ft during t = 40 to 50 days

4 indicates 0.1 ft water added to groundwater during t=0 to 10 days only.
5 indicates 0.2 ft water added to groundwater during t=10 to 20 days only.
6 indicates 0.4 ft water added to groundwater during t=20 to 30 days only.

[l] Withdrawal area net Q (negative input)
0 indicates no withdrawals.
1 indicates withdrawal of same time schedule and amounts as the No. 1 condition under "Irrigated Area Input Q."

APPENDIX D

Table 14. Results of one-dimensional model analyses.

Time (days)	Calculated groundwater outflow to stream (percent of input Q)																		
	Model Numbers																		
	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119
0-10	1.31	0.30	0.07	0.02	1.74	0.43	0.12	2.55	0.74	0.03	0.09	0.54	3.20	1.22	1.59	6.23	0.33	0.30	1.75
10-20	3.35	1.01	0.32	0.13	4.42	1.45	0.52	6.37	2.39	0.14	0.35	1.50	6.10	3.11	4.04	5.71	0.34	0.30	4.46
20-30	7.25	2.48	0.90	0.39	9.54	3.52	1.39	13.59	5.63	0.35	0.75	2.62	8.16	6.75	8.71	12.11	0.25	0.20	9.67
30-40	7.09	3.65	1.66	0.85	9.15	5.02	2.44	12.44	7.52	0.69	1.29	3.71	9.62	6.63	8.41	11.28	1.93	1.82	9.44
40-50	6.24	4.26	2.40	1.42	7.80	5.63	3.32	9.96	7.83	1.13	1.91	4.72	10.68	5.87	7.25	9.28	3.29	3.09	8.29
50-60	4.74	4.31	2.94	1.99	5.59	5.40	3.81	6.41	6.88	1.64	2.47	5.08	8.27	4.52	5.31	6.25	4.08	3.86	6.27
60-70	4.02	4.14	3.28	2.49	4.47	4.89	3.98	4.67	5.70	2.12	2.90	4.92	6.12	3.90	4.33	4.71	4.03	3.86	5.28
70-80	3.57	3.91	3.45	2.86	3.74	4.35	3.93	3.61	4.71	2.53	3.17	4.53	4.49	3.50	3.70	3.74	3.84	3.73	4.63
80-90	3.24	3.68	3.50	3.12	3.25	3.89	3.79	2.92	3.95	2.84	3.30	4.10	3.50	3.22	3.24	3.08	3.64	3.57	4.14
90-100	2.98	3.47	3.48	3.26	2.84	3.51	3.62	2.44	3.39	3.05	3.35	3.71	2.83	3.00	2.90	2.61	3.44	3.41	3.75
100-110	2.78	3.28	3.41	3.37	2.55	3.21	3.43	2.10	2.96	2.17	3.33	3.37	2.38	2.81	2.63	2.27	3.25	3.25	3.41
110-120	2.60	3.11	3.31	3.31	2.32	2.95	3.26	1.85	2.64	3.22	3.27	3.09	2.05	2.65	2.41	2.01	3.08	3.10	3.11
120-130	2.44	2.94	3.20	3.27	2.14	2.74	3.09	1.66	2.38	3.21	3.18	2.85	1.81	2.50	2.24	1.81	2.92	2.95	2.85
130-140	2.30	2.79	3.08	3.19	1.99	2.56	2.93	1.51	2.18	3.17	3.08	2.65	1.62	2.37	2.09	1.66	2.77	2.81	2.61
140-150	2.18	2.65	2.96	3.10	1.86	2.41	2.78	1.39	2.02	3.10	2.97	2.48	1.48	2.25	1.96	1.53	2.64	2.68	2.40
150-160	2.07	2.52	2.83	2.99	1.74	2.27	2.65	1.29	1.88	3.01	2.86	2.34	1.36	2.13	1.84	1.43	2.51	2.55	2.20
160-170	1.96	2.40	2.70	2.88	1.65	2.14	2.52	1.20	1.76	2.91	2.74	2.21	1.27	2.03	1.74	1.34	2.38	2.43	2.03
170-180	1.86	2.28	2.59	2.76	1.56	2.03	2.40	1.13	1.66	2.80	2.63	2.09	1.19	1.93	1.65	1.26	2.27	2.31	1.86
180-210	4.85	5.96	6.80	7.31	4.03	5.28	6.28	2.91	4.28	7.46	6.94	5.43	3.03	5.03	4.29	3.24	5.92	6.05	4.44
210-240	4.22	5.18	5.93	6.41	3.50	4.59	5.48	2.52	3.71	6.57	6.10	4.73	2.62	4.37	3.73	2.81	5.15	5.27	3.53
240-270	3.67	4.51	5.18	5.62	3.04	4.00	4.79	2.19	3.23	5.77	5.35	4.13	2.28	3.81	3.26	2.44	4.49	4.60	2.81
270-300	3.20	3.93	4.52	4.91	2.65	3.49	4.18	1.91	2.82	5.07	4.69	3.61	1.99	3.32	2.83	2.13	3.91	4.00	2.23
300-330	2.78	3.43	3.95	4.30	2.32	3.04	3.66	1.67	2.46	4.45	4.11	3.16	1.74	2.89	2.48	1.86	3.41	3.50	1.78
330-360	2.43	2.99	3.45	3.76	2.02	2.66	3.20	1.46	2.16	3.90	3.60	2.77	1.52	2.53	2.16	1.63	2.97	3.05	1.42

Table 14. (continued)

	Calculated groundwater outflow to stream (percent of input Q)																		
	Model Numbers																		
Time (days)	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138
0-10	0.44	0.14	2.56	0.74	4.37	0.33	0.90	1.90	3.04	0.00	0.01	0.30	1.18	0.00	0.00	0.24	1.57	1.31	1.31
10-20	1.51	0.62	6.38	2.41	10.34	0.89	2.31	4.80	7.62	0.00	0.06	1.13	3.82	0.00	0.00	0.86	4.09	3.34	3.34
20-30	3.71	1.70	13.63	5.69	21.50	1.98	5.02	10.39	16.40	0.00	0.19	2.92	9.02	0.00	0.03	1.79	6.75	7.23	7.23
30-40	5.44	3.09	12.54	7.69	17.25	2.13	4.99	10.04	15.44	0.00	0.40	4.73	12.16	0.00	0.08	2.92	9.15	7.02	7.02
40-50	6.32	4.34	10.19	8.14	12.05	1.97	4.41	8.78	13.02	0.00	0.66	5.98	12.83	0.00	0.15	4.15	11.18	6.17	6.17
50-60	6.34	5.16	6.71	7.34	6.02	1.57	3.38	6.60	9.09	0.00	0.94	6.45	11.40	0.00	0.26	5.13	11.27	4.68	4.68
60-70	6.00	5.54	5.06	6.32	3.79	1.33	2.86	5.54	7.01	0.01	1.18	6.40	9.49	0.00	0.39	5.70	10.10	3.97	3.97
70-80	5.57	5.58	4.09	5.45	2.73	1.17	2.54	4.84	5.55	0.02	1.38	6.10	7.72	0.00	0.55	5.87	8.54	3.53	3.53
80-90	5.14	5.42	3.45	4.77	2.14	1.06	2.31	4.30	4.44	0.03	1.53	5.69	6.24	0.00	0.72	5.60	7.04	3.21	3.21
90-100	4.73	5.16	3.01	4.24	1.78	0.97	2.14	3.86	3.56	0.04	1.64	5.24	5.04	0.00	0.88	5.51	5.74	2.96	2.96
100-110	4.35	4.84	2.67	3.81	1.53	0.91	2.00	3.49	2.86	0.05	1.72	4.81	4.06	0.00	1.04	5.17	4.66	2.75	2.75
110-120	3.99	4.51	2.40	3.46	1.36	0.85	1.88	3.16	2.31	0.07	1.39	4.40	3.28	0.00	1.18	4.80	3.87	2.58	2.58
120-130	3.67	4.18	2.18	3.16	1.22	0.80	1.78	2.86	1.86	0.08	1.80	4.02	2.64	0.00	1.31	4.43	3.06	2.43	2.43
130-140	3.38	3.87	1.99	2.89	1.10	0.77	1.70	2.60	1.50	0.10	1.82	3.66	2.13	0.00	1.41	4.07	2.48	2.29	2.29
140-150	3.10	3.57	1.83	2.65	1.00	0.74	1.62	2.37	1.21	0.11	1.82	3.34	1.72	0.00	1.50	3.73	2.01	2.17	2.17
150-160	2.86	3.30	1.68	2.44	0.92	0.71	1.56	2.15	0.98	0.13	1.81	3.05	1.39	0.00	1.56	3.41	1.63	2.06	2.06
160-170	2.63	3.04	1.54	2.25	0.85	0.68	1.50	1.97	0.79	0.15	1.80	2.78	1.12	0.01	1.61	3.12	1.32	1.96	1.96
170-180	2.42	2.80	1.42	2.07	0.78	0.66	1.45	1.79	0.64	0.16	1.78	2.53	0.91	0.01	1.65	2.86	1.07	1.86	1.86
180-210	5.77	6.70	3.38	4.94	1.86	1.81	3.95	4.15	1.16	0.60	5.10	5.90	1.59	0.08	5.01	6.69	1.88	4.86	4.86
210-240	4.59	5.34	2.70	3.94	1.49	1.68	3.62	3.22	0.65	0.70	4.82	4.57	0.93	0.14	4.92	5.22	1.10	4.23	4.23
240-270	3.65	4.26	2.15	3.14	1.19	1.57	3.34	2.49	0.38	0.79	4.53	3.55	0.54	0.20	4.75	4.07	0.65	3.69	3.69
270-300	2.91	3.40	1.71	2.51	0.95	1.48	3.09	1.94	0.22	0.86	4.25	2.76	0.32	0.27	4.53	3.18	0.38	3.22	3.22
300-330	2.32	2.71	1.37	2.00	0.76	1.40	2.86	1.50	0.13	0.92	3.97	2.15	0.19	0.34	4.29	2.48	0.22	2.82	2.82
330-360	1.85	2.16	1.09	1.60	0.60	1.34	2.65	1.17	0.08	0.97	3.70	1.67	0.11	0.42	4.04	1.93	0.13	2.46	2.46

Table 14. (continued)

Calculated groundwater outflow to stream (percent of input Q)

Time (days)	Model Numbers																			
	139	141	142	143	144	146	147	148	151	152	153	154	155	156	158	159	160	161	162	163
0-10	1.31	1.50	1.66	1.17	0.85	1.40	1.20	1.22	1.31	1.31	13.14	0.00		1.31	4.98	2.62	1.05	0.88	0.66	0.53
10-20	3.36	3.79	4.16	3.03	2.28	3.82	3.08	3.13	3.44	3.36	7.11	13.14		3.34	12.17	6.67	2.68	2.23	1.67	1.34
20-30	7.31	8.19	8.97	6.60	5.05	7.70	6.70	6.80	7.23	7.31	5.28	7.14	13.14	7.21	25.16	14.42	5.80	4.84	3.63	2.94
30-40	7.22	7.88	8.51	6.64	5.44	7.46	6.61	6.73	7.02	7.22	4.38	5.29	7.20	7.00	22.01	13.93	5.67	4.73	3.55	2.84
40-50	6.38	7.29	7.29	6.00	5.16	6.52	5.86	5.98	6.17	6.38	3.82	4.39	5.33	6.13	15.98	11.99	4.99	4.16	3.12	2.50
50-60	4.86	5.08	5.31	4.73	4.31	4.91	4.50	4.61	4.68	4.86	3.44	3.83	4.22	4.65	8.29	8.68	3.79	3.16	2.37	1.90
60-70	4.18	4.26	4.38	4.10	3.84	4.15	3.83	3.95	3.97	4.11	3.14	3.44	3.85	3.95	4.66	6.91	3.22	2.69	2.01	1.61
70-80	3.65	3.73	3.79	3.69	3.51	3.66	3.42	3.52	3.53	3.65	2.91	3.15	3.46	3.51	2.67	5.67	2.86	2.39	1.79	1.43
80-90	3.31	3.35	3.37	3.38	3.26	3.31	3.12	3.22	3.21	3.31	2.71	2.91	3.16	3.19	1.54	4.70	2.61	2.17	1.63	1.30
90-100	3.04	3.06	3.04	3.14	3.05	3.04	2.88	2.97	2.96	3.04	2.55	2.72	2.92	2.94	0.89	3.92	2.41	2.01	1.51	1.21
100-110	2.82	2.82	2.78	2.93	2.87	2.82	2.69	2.77	2.75	2.82	2.40	2.55	3.67	2.74	0.51	3.28	2.25	1.88	1.41	1.13
110-120	2.64	2.62	2.56	2.74	2.71	2.63	2.53	2.60	2.58	2.64	2.27	2.41	2.56	2.52	0.30	2.75	2.12	1.77	1.33	1.06
120-130	2.48	2.45	2.37	2.58	2.56	2.47	2.39	2.45	2.43	2.48	2.16	2.28	2.41	2.42	0.17	2.90	2.01	1.68	1.26	1.01
130-140	2.33	2.30	2.21	2.44	2.43	2.32	2.26	2.32	2.29	2.33	2.05	2.18	2.28	2.28	0.10	1.93	1.91	1.60	1.20	0.96
140-150	2.20	2.16	2.06	2.31	2.31	2.19	2.12	2.20	2.17	2.20	1.95	2.05	2.16	2.17	0.06	1.62	1.82	1.53	1.15	0.92
150-160	2.08	2.04	1.94	2.18	2.19	2.07	2.04	2.09	2.06	2.08	1.85	1.95	2.05	2.06	0.03	1.36	1.74	1.47	1.10	0.88
160-170	1.97	1.92	1.82	2.07	2.09	1.96	1.94	1.98	1.96	1.97	1.77	1.86	1.95	1.95	0.02	1.15	1.67	1.42	1.06	0.85
170-180	1.87	1.82	1.71	1.96	1.99	1.86	1.85	1.89	1.86	1.87	1.68	1.77	1.86	1.86	0.01	0.96	1.61	1.37	1.03	0.82
180-210	4.84	4.68	4.38	5.08	5.23	4.80	4.87	4.93	4.86	4.84	4.41	4.63	4.85		0.01	1.85	4.35	3.75	2.84	2.27
210-240	4.18	4.02	3.75	4.39	4.58	4.14	4.28	4.32	4.23	4.18	3.86	4.04	4.43		0.00	1.18	3.94	3.45	2.63	2.11
240-270	4.18	3.46	3.23	3.80	4.03	3.58	3.76	3.76	3.69	3.61	3.38	3.53	3.70		0.00	0.76	3.58	3.19	2.46	1.98
270-300	3.14	2.98	2.78	3.29	3.54	3.10	3.30	3.28	3.26	3.18	2.95	3.09	3.22		0.00	0.48	3.26	2.97	2.32	1.86
300-330	2.72	2.57	2.40	2.85	3.12	2.68	2.91	2.87	2.82	2.72	2.59	2.70	2.82		0.00	0.31	2.97	2.77	2.20	1.77
330-360	2.37	2.22	2.07	2.47	2.75	2.33	2.56	2.51	2.46	2.37	2.26	2.36	2.46		0.00	0.20	2.71	2.58	2.09	1.69

APPENDIX E

Table 15. Description of two-dimensional models analyzed[a].

Model no.	Perme-ability pattern[b]	Specific yield pattern[c]	Lateral boundaries[d]	Initial water table[e]	Bed-rock[f]	Land surface[g]	Δx[h]	Δy[i]	Net Q-time distr.[j]	Net Q-areal distr.[k]
201	1	1	1	1	1	1	1	1	A,B,C	W
202	1	1	1	2	2	2	1	1	A,B,C	W
203	1	1	1	3	3	3	1	1	A,B,C	W
204	1	1	1	1	1	1	2	1	A,B,C	W
205	1	1	1	2	2	2	2	1	A,B,C	W
206	1	1	1	3	3	3	2	1	A,B,C	W
207	2	1	1	1	1	1	2	1	A,B,C	W
208	2	1	1	3	3	3	2	1	A,B,C	W
209	3	1	1	3	3	3	2	1	A,B,C	W
210	4	1	1	3	3	3	2	1	A,B,C	W
211	5	1	1	3	3	3	2	1	A,B,C	W
212	1	1	2	1	1	1	2	1	A,B,C	W
213	1	1	1	3	3	3	2	1	0	0
214	1	1	1	1	4	1	2	1	A,B,C	W
215	1	1	1	1	5	1	2	1	A,B,C	W
216	1	1	1	1	1	1	2	1	A,B,C	W
217	2	1	1	1	1	1	2	1	A,B,C	W
218	3	1	1	1	1	1	2	1	A,B,C	W
219	4	1	1	1	1	1	2	1	A,B,C	W
220	5	1	1	1	1	1	2	1	A,B,C	W
221	1	1	2	3	3	3	2	1	0,A,B,C	0,W
222	1	1	3	3	3	3	2	1	0,A,B,C	0,W
223										
224	1	1	1	1	1	1	2	1	A,B,C	X
225	2	1	1	1	1	1	2	1	A,B,C	X
226	3	1	1	1	1	1	2	1	A,B,C	X
227	4	1	1	1	1	1	2	1	A,B,C	X
228	5	1	1	1	1	1	2	1	A,B,C	X
229	1	1	1	1	1	1	2	1	C	Y
230	1	1	1	1	1	1	2	1	C	Z

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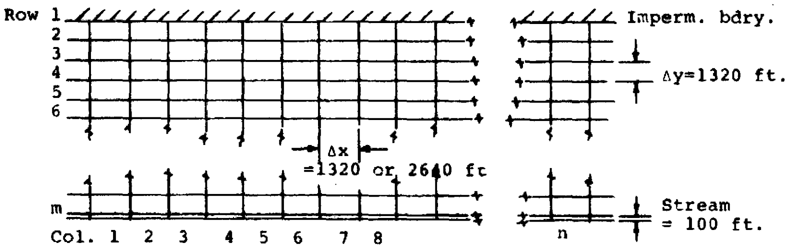
[a] Basic grid arrangement for two-dimensional models.



[b] Permeability

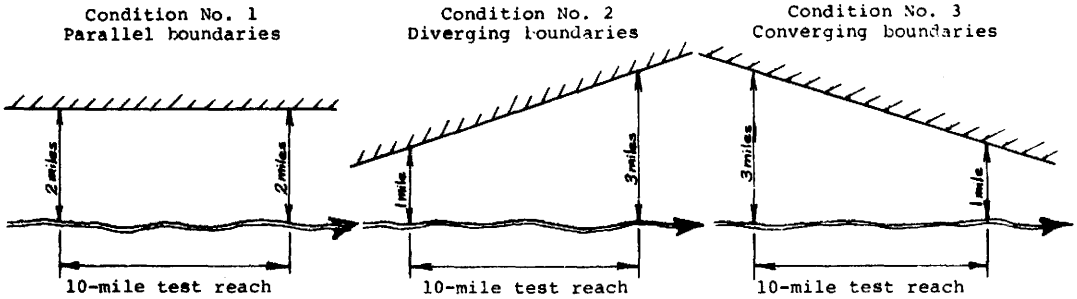
	Pattern No. 1	2	3	4	5
Row No. 2	0.01	0.006	0.002	0.006	0.001
3	0.01	0.007	0.004	0.008	0.006
4	0.01	0.008	0.006	0.010	0.011
5	0.01	0.009	0.008	0.013	0.016
6	0.01	0.010	0.010	0.016	0.022
7	0.01	0.011	0.012	0.013	0.016
8	0.01	0.012	0.014	0.010	0.011
9	0.01	0.013	0.016	0.003	0.006
10	0.01	0.014	0.018	0.006	0.001

(All values in feet per second)

[c] Specific yield
Pattern no. 1--Uniform throughout model at 0.20.

Appendix E (continued)

[d] Lateral boundaries


Condition No. 1 Parallel boundaries

Condition No. 2 Diverging boundaries

Condition No. 3 Converging boundaries

[e] Initial water table

Condition No. 1--Level with 50 feet of saturated thickness.

Condition No. 2--Sloping in the x-direction at 8 feet per mile, with 50 feet of saturated thickness.

Condition No. 3--Sloping in the x-direction at 8 feet per mile and in the y-direction (toward the river) at 8 feet per mile. Average initial saturated thickness of 50 feet.

[f] Bedrock configuration

Condition No. 1--Level.

Condition No. 2--Slope in x-direction (downstream) at 8 feet per mile.

Condition No. 3--Slope in x-direction and in y-direction (downstream and toward river) at 8 feet per mile.

Condition No. 4--No slope in x-direction, slope in y-direction <u>away</u> from the river at 8 feet per mile.

Condition No. 5--No slope in x-direction, slope in y-direction away from the river at 16 feet per mile to low point in Row No. 6, then upwards at 16 feet per mile to Row 2.

[g] Land surface

Condition No. 1--Level, 10 feet above initial water table elevation.

Condition No. 2--Slope in x-direction, 8 feet per mile.

Condition No. 3--Slope in x-direction at 8 feet per mile downstream and slope in y-direction at 8 feet per mile toward river.

[h] Delta x

Condition No. 1--Δx = 1320 feet.

Condition No. 2--Δx = 2640 feet.

[i] Delta y

Condition No. 1--Δy = 1320 feet.

[j] Net Q input, time distribution

Input 0--No water added to groundwater.

Input A--One foot of water added to groundwater initial water table t = 0.

Input B--0.10 ft. added during t = 0 to 10 days.
0.30 ft. added during t = 10 to 20 days.
0.20 ft. added during t = 20 to 30 days.
0.15 ft. added during t = 30 to 40 days.
0.10 ft. added during t = 40 to 50 days.
0.05 ft. added during t = 50 to 60 days.
0.05 ft. added during t = 60 to 70 days.
0.05 ft. added during t = 70 to 80 days,

Input C--0.10 ft. added during t = 0 to 10 days.
0.20 ft. added during t = 10 to 20 days.
0.40 ft. added during t = 20 to 30 days.
0.20 ft. added during t = 30 to 40 days.
0.10 ft. added during t = 40 to 50 days.

[k] Net Q input, areal distribution

Input W--Uniform over model area.

Input X--Uniform over all grid cells except the center grid (row 6, column 13 for the Δx = 2640 ft. models). A negative Q of 20 acre-feet per day is superimposed on this grid for the full period of calculation.

Input Y--The "C" time distribution of water input is applied to 75% of the grid cells chosen randomly from a uniform distribution.

Input Z--The "C" time distribution of water input is applied to 50% of the grid cells chosen randomly from a uniform distribution.

APPENDIX F

Table 16. Results of two-dimensional model analyses ("A" time distribution of Q).

Calculated groundwater outflow to stream (percent of input Q)

Model numbers

Time (days)	201A	202A	203A	204A	205A	206A	207A	208A	209A	210A	211A	212A	214A
0-10	13.03	13.03	22.24	13.03	13.03	22.24	15.00	26.04	29.29	19.35	18.25	13.03	11.92
10-20	7.46	7.45	15.27	7.46	7.46	15.28	8.17	17.09	18.47	14.72	14.02	7.45	7.05
20-30	5.49	5.48	12.80	5.49	5.48	12.81	5.90	14.01	14.78	12.81	12.40	5.46	5.10
30-40	4.51	4.50	11.49	4.51	4.51	11.50	4.79	12.35	12.76	11.72	11.45	4.46	4.27
40-50	3.92	3.90	10.59	3.92	3.91	10.60	4.11	11.21	11.39	10.93	10.73	3.84	4.72
50-60	3.51	3.49	9.88	3.51	3.50	9.89	3.64	10.34	10.35	10.26	10.12	3.40	3.34
60-70	3.20	3.18	9.28	3.20	3.19	9.29	3.29	9.61	9.51	9.67	9.57	3.06	3.06
70-80	2.96	2.93	8.75	2.96	2.94	8.76	3.02	8.98	8.80	9.13	9.06	2.80	2.84
80-90	2.76	2.72	8.26	2.76	2.74	8.27	2.79	8.42	8.19	8.63	8.58	2.58	2.65
90-100	2.58	2.55	7.82	2.58	2.57	7.83	2.59	7.92	7.66	8.16	8.14	2.38	2.49
100-110	2.43	2.40	7.41	2.43	2.42	7.42	2.42	7.46	7.18	7.73	7.72	2.22	2.36
110-120	2.29	2.26	7.03	2.29	2.28	7.04	2.28	7.04	6.75	7.32	7.33	2.08	2.24
120-130	2.17	2.14	6.68	2.17	2.16	6.68	2.14	6.64	6.36	6.94	6.97	1.95	2.12
130-140	2.06	2.03	6.34	2.06	2.04	6.34	2.02	6.29	6.00	6.58	6.62	1.83	2.02
140-150	1.95	1.92	6.03	1.95	1.94	6.03	1.91	5.96	5.67	6.25	6.30	1.73	1.93
150-160	1.85	1.83	5.74	1.85	1.84	5.75	1.81	5.64	5.36	5.93	6.00	1.63	1.84
160-170	1.76	1.74	5.46	1.76	1.75	5.45	1.72	5.35	5.08	5.63	5.71	1.55	1.76
170-180	1.68	1.65	5.20	1.68	1.55	5.19	1.63	5.08	4.82	5.36	5.44	1.47	1.68
180-210	4.38	4.31	13.68	4.38	4.35	13.63	4.22	13.21	12.53	13.99	14.31	3.82	4.48
210-240	3.80	3.76	11.97	3.80	3.79	11.90	3.66	11.44	10.86	12.16	12.53	3.34	3.97
240-270	3.31	3.29	10.50	3.31	3.30	10.42	3.19	9.93	9.44	10.60	11.00	2.94	3.54
270-300	2.89	2.88	9.24	2.89	2.88	9.14	2.78	8.65	8.23	9.25	9.68	2.60	3.16
300-330	2.52	2.53	8.15	2.52	2.52	8.04	2.43	7.54	7.12	8.10	8.55	2.31	2.83
330-360	2.20	2.22	7.21	2.20	2.21	7.08	2.14	6.50	6.30	7.10	7.56	2.06	2.54

Time (days)	215A	216A	217A	218A	219A	220A	221A	222A	224A	225A	226A	227A	228A
0-10	11.96	13.03	15.00	16.67	11.56	8.44	21.98	21.96	13.80	15.89	17.65	12.24	8.94
10-20	7.05	7.46	8.17	8.76	7.11	5.97	14.98	15.04	7.88	8.63	9.20	7.51	6.31
20-30	5.25	5.48	5.90	6.19	5.42	4.84	12.40	12.52	5.78	6.21	6.52	5.71	5.11
30-40	4.36	4.51	4.79	4.96	4.56	4.20	10.96	11.16	4.73	5.03	5.20	4.79	4.42
40-50	3.81	3.91	4.11	4.21	4.02	3.78	9.95	10.24	4.10	4.30	4.39	4.21	3.97
50-60	3.43	3.50	3.64	3.68	3.64	3.47	9.15	9.53	3.65	3.79	3.83	3.80	3.63
60-70	3.14	3.19	3.29	3.30	3.34	3.22	8.48	8.94	3.32	3.41	3.40	3.48	3.37
70-80	2.91	2.95	3.01	2.98	3.10	3.01	7.89	8.44	3.05	3.11	3.07	3.21	3.13
80-90	2.72	2.75	2.78	2.73	2.89	2.83	7.37	8.00	2.83	2.86	2.79	2.99	2.93
90-100	2.56	2.57	2.59	2.52	2.71	2.67	6.90	7.60	2.64	2.65	2.57	2.79	2.76
100-110	2.42	2.42	2.42	2.34	2.55	2.52	6.46	7.25	2.48	2.47	2.37	2.62	2.60
110-120	2.36	2.29	2.27	2.18	2.41	2.39	6.07	6.93	2.33	2.30	2.20	2.46	2.46
120-130	2.10	2.17	2.13	2.04	2.23	2.27	5.71	6.63	2.19	2.16	2.05	2.32	2.32
130-140	2.06	2.06	2.01	1.91	2.16	2.16	5.37	6.36	2.08	2.03	1.91	2.19	2.20
140-150	1.97	1.95	1.90	1.30	2.04	2.06	5.06	6.11	1.95	1.90	1.79	2.07	2.09
150-160	1.88	1.36	1.80	1.69	1.94	1.96	4.77	5.78	1.85	1.79	1.67	1.95	1.98
160-170	1.79	1.77	1.70	1.60	1.84	1.87	4.51	5.65	1.75	1.69	1.57	1.84	1.88
170-180	1.71	1.69	1.60	1.51	1.75	1.78	4.25	5.45	1.66	1.59	1.48	1.74	1.79
180-210	4.52	4.44	4.16	3.89	4.53	4.70	10.97	14.90	4.26	4.04	3.73	4.46	4.66
210-240	3.99	3.90	3.59	3.35	3.93	4.13	9.41	13.63	3.65	3.41	3.14	3.80	4.04
240-270	3.54	3.44	3.10	2.89	3.41	3.64	8.08	12.54	3.12	2.88	2.64	3.23	3.50
270-300	3.14	3.04	2.68	2.50	2.96	3.22	6.93	11.60	2.67	2.42	2.22	2.75	3.04
200-330	2.80	2.70	2.32	2.16	2.58	2.84	5.94	10.78	2.27	2.03	1.86	2.33	2.63
330-360	2.51	2.40	2.01	1.87	2.24	2.52	5.09	10.06	1.93	1.69	1.54	1.96	2.28

APPENDIX F

Table 17. Results of two-dimensional model analyses ("B" time distribution of Q).

	Calculated groundwater outflow to stream (percent of input Q)												
	Model numbers												
Time (days)	201B	202B	203B	204B	205B	206B	207B	208B	209B	210B	211B	212B	214B
0-10	1.23	1.23	9.69	1.23	1.23	9.70	1.42	11.60	13.26	8.66	7.95	1.23	1.11
10-20	4.44	4.44	11.92	4.44	4.44	11.92	5.09	13.69	15.09	11.20	10.52	4.44	4.04
20-30	5.28	5.28	12.43	5.24	5.28	12.44	5.92	13.89	14.92	12.06	11.50	5.27	4.87
30-40	5.48	5.48	12.39	5.43	5.48	12.39	6.07	13.58	14.31	12.25	11.80	5.47	5.10
40-50	5.25	5.23	11.92	5.19	5.24	11.92	5.74	12.85	13.32	11.96	11.60	5.21	4.91
50-60	4.66	4.65	11.08	4.61	4.66	11.08	5.03	11.77	12.01	11.26	11.00	4.61	4.39
60-70	4.42	4.40	10.55	4.37	4.41	10.56	4.73	11.10	11.21	10.79	10.58	4.34	4.17
70-80	4.30	4.28	10.17	4.26	4.30	10.17	4.58	10.61	10.63	10.42	10.25	4.21	4.07
80-90	3.63	3.61	9.28	3.59	3.62	9.23	3.79	9.51	9.39	9.55	9.45	3.51	3.47
90-100	3.23	3.21	8.55	3.20	3.22	8.56	3.33	8.74	8.55	8.88	8.83	3.09	3.10
100-110	2.96	2.92	8.01	2.92	2.94	8.01	3.02	8.12	7.90	8.33	8.30	2.79	2.84
110-120	2.77	2.72	7.54	2.71	2.73	7.54	2.77	7.60	7.35	7.84	7.84	2.56	2.64
120-130	2.56	2.53	7.12	2.54	2.54	7.12	2.57	7.14	6.87	7.40	7.42	2.36	2.48
130-140	2.40	2.39	6.74	2.38	2.39	6.74	2.40	6.63	6.45	7.00	7.03	2.20	2.34
140-150	2.26	2.22	6.39	2.25	2.25	6.39	2.27	6.43	6.07	6.63	6.67	2.05	2.22
150-160	2.14	2.11	6.07	2.13	2.13	6.06	2.10	5.99	5.72	6.28	6.34	1.92	2.11
160-170	2.03	2.00	5.76	2.02	2.02	5.76	2.00	5.67	5.40	5.96	6.03	1.81	2.01
170-180	1.92	1.90	5.48	1.92	1.91	5.47	1.89	5.37	5.11	5.66	5.74	1.70	1.91
180-210	5.00	4.93	14.38	4.99	4.97	14.33	4.87	13.94	13.24	14.75	15.06	4.39	5.05
210-240	4.34	4.29	12.56	4.35	4.32	12.50	4.21	12.05	11.44	12.80	13.16	3.81	4.47
240-270	3.77	3.74	11.01	3.79	3.76	10.93	3.65	10.45	9.93	11.14	11.57	3.32	3.97
270-300	3.28	3.27	9.68	3.31	3.28	9.58	3.18	9.08	8.64	9.72	10.14	2.92	3.53
300-330	2.86	2.87	8.53	2.89	2.87	8.42	2.77	7.92	7.54	8.50	8.95	2.58	3.16
330-360	2.49	2.52	7.54	2.53	2.51	7.41	2.43	6.92	6.60	7.45	7.91	2.29	2.83
Time (days)	**215B**	**216B**	217B	**218B**	**219B**	**220B**	**221B**	**222B**	**224B**	**225B**	**226B**	**227B**	**228B**
0-10	1.12	1.23	1.42	1.58	1.09	7.87	9.65	9.66	1.30	1.50	1.67	1.15	0.83
10-20	4.06	4.44	5.09	5.63	3.98	2.95	11.72	11.77	4.69	5.37	5.94	4.20	3.12
20-30	4.91	5.28	5.92	6.45	4.87	3.85	12.08	12.19	5.56	6.24	6.79	5.13	4.05
30-40	5.15	5.48	6.07	6.54	5.17	4.26	11.91	12.08	5.77	6.38	6.87	5.44	4.48
40-50	4.97	5.24	5.74	6.11	5.05	4.32	11.32	11.58	5.50	6.02	6.40	5.30	4.53
50-60	4.46	4.66	5.03	5.28	4.59	4.07	10.39	10.74	4.88	5.26	5.51	4.80	4.26
60-70	4.24	4.41	4.72	4.93	4.39	3.96	9.79	10.23	4.61	4.93	5.13	4.59	4.14
70-80	4.15	4.30	4.58	4.74	4.31	3.92	9.34	9.87	4.48	4.77	4.93	4.49	4.09
80-90	3.55	3.61	3.78	3.84	3.72	3.51	8.36	8.98	3.76	3.93	3.97	3.87	3.65
90-100	3.18	3.23	3.33	3.33	3.35	3.22	7.66	8.35	3.33	3.43	3.43	3.47	3.34
100-110	2.92	2.95	3.01	2.99	3.08	2.99	7.09	7.86	3.03	3.10	3.06	3.18	3.09
110-120	2.71	2.73	2.77	2.71	2.87	2.80	6.60	7.45	2.80	2.83	2.77	2.95	2.89
120-130	2.54	2.55	2.56	2.50	2.68	2.64	6.17	7.08	2.60	2.61	2.53	2.75	2.71
130-140	2.40	2.40	2.39	2.31	2.52	2.50	5.78	6.75	2.44	2.43	2.33	2.57	2.55
140-150	2.27	2.27	2.24	2.15	2.38	2.36	5.43	6.46	2.29	2.26	2.16	2.42	2.41
150-160	2.15	2.14	2.11	2.01	2.24	2.24	5.10	6.19	2.15	2.12	2.01	2.28	2.28
160-170	2.04	2.04	1.98	1.88	2.12	2.13	4.80	5.94	2.03	1.99	1.87	2.15	2.16
170-180	1.95	1.93	1.87	1.77	2.01	2.03	4.53	5.71	1.92	1.87	1.75	2.02	2.05
180-210	5.12	5.06	4.81	4.52	5.21	5.32	11.63	15.55	4.92	4.72	4.40	5.17	5.32
210-240	4.51	4.43	4.13	3.87	4.50	4.67	9.95	14.17	4.21	3.99	3.69	4.41	4.60
240-270	3.99	3.81	3.56	3.32	3.90	4.10	8.53	12.99	3.60	3.37	3.10	3.75	3.99
270-300	3.53	3.51	3.07	2.87	3.39	3.62	7.31	11.97	3.08	2.64	2.60	3.19	3.46
300-330	3.14	3.04	2.66	2.48	2.94	3.20	6.27	11.10	2.63	2.39	2.20	2.71	3.00
330-360	2.81	2.70	2.30	2.15	2.56	2.83	5.37	10.34	2.24	2.00	1.83	2.30	2.60

APPENDIX F

Table 18. Results of two-dimensional model analyses ("C" time distribution of Q).

	Calculated groundwater outflow to stream (percent of input Q)													
	Model numbers													
Time (days)	201C	202C	203C	204C	205C	206C	207C	208C	209C	210C	211C	212C	214C	215C
0-10	1.23	1.23	9.69	1.23	1.23	9.70	1.42	11.60	13.26	8.66	7.95	1.23	1.11	1.11
10-20	3.21	3.21	10.70	3.20	3.21	10.69	3.66	12.27	13.51	10.11	9.52	3.21	2.93	2.94
20-30	7.00	7.00	14.10	6.97	7.00	14.10	7.95	15.85	17.15	13.48	12.78	6.99	6.41	6.44
30-40	7.09	7.07	14.03	7.01	7.08	14.04	7.88	15.42	16.31	13.77	13.22	7.07	6.58	6.64
40-50	6.30	6.28	13.03	6.22	6.30	13.03	6.89	14.05	14.59	13.04	12.64	6.27	5.91	5.98
50-60	4.85	4.83	11.31	4.78	4.84	11.32	5.18	11.97	12.16	11.56	11.33	4.80	4.59	4.68
60-70	4.09	4.07	10.25	4.04	4.08	10.26	4.31	10.71	10.73	10.58	10.43	4.01	3.89	3.97
70-80	3.61	3.59	9.48	3.57	3.60	9.48	3.76	9.80	9.71	9.84	9.73	3.50	3.44	3.53
80-90	3.27	3.24	8.85	3.23	3.26	8.86	3.37	9.08	8.91	9.21	9.14	3.14	3.13	3.21
90-100	3.01	2.98	8.31	2.98	3.00	8.32	3.07	8.47	8.25	8.66	8.62	2.85	2.89	2.96
100-110	2.79	2.76	7.84	2.77	2.78	7.84	2.83	7.93	7.68	8.17	8.15	2.62	2.69	2.76
110-120	2.61	2.58	7.41	2.59	2.60	7.41	2.63	7.45	7.18	7.71	7.71	2.42	2.53	2.59
120-130	2.45	2.43	7.01	2.44	2.44	7.01	2.46	7.02	6.74	7.29	7.31	2.25	2.39	2.44
130-140	2.32	2.28	6.65	2.30	2.30	6.65	2.30	6.62	6.34	6.91	6.94	2.10	2.26	2.31
140-150	2.19	2.16	6.31	2.18	2.18	6.31	2.17	6.25	5.97	6.55	6.59	1.97	2.15	2.20
150-160	2.07	2.05	5.99	2.07	2.06	5.99	2.05	5.92	5.64	6.21	6.27	1.85	2.05	2.09
160-170	1.97	1.94	5.70	1.96	1.96	5.69	1.93	5.60	5.33	5.89	5.96	1.75	1.95	1.99
170-180	1.87	1.84	5.42	1.87	1.86	5.41	1.83	5.31	5.05	5.59	5.67	1.65	1.86	1.90
180-210	4.86	4.80	14.24	4.87	4.84	14.19	4.73	13.79	13.09	14.60	14.91	4.26	4.93	4.99
210-240	4.22	4.18	12.45	4.24	4.20	12.38	4.09	11.93	11.32	12.67	13.04	3.70	4.37	4.40
240-270	3.67	3.65	10.91	3.70	3.66	10.83	3.55	10.35	9.83	11.03	11.43	3.24	3.89	3.89
270-300	3.20	3.19	9.59	3.23	3.20	9.49	3.09	9.00	8.56	9.62	10.05	2.85	3.46	3.45
300-330	2.79	2.80	8.46	2.82	2.79	8.34	2.70	7.84	7.48	8.42	8.87	2.52	3.09	3.07
330-360	2.43	2.46	7.48	2.47	2.45	7.35	2.37	6.85	6.54	7.38	7.84	2.24	2.77	2.74

Time (days)	216C	217C	218C	219C	220C	221C	222C	224C	225C	226C	227C	228C	229C[a]	230C[a]
0-10	1.23	1.42	1.58	1.09	0.79	9.65	9.66	1.30	1.50	1.67	1.15	0.83	1.3	1.3
10-20	3.21	3.66	4.04	2.88	2.16	10.51	10.56	3.38	3.86	4.25	3.04	2.28	3.2	3.2
20-30	7.00	7.95	8.74	6.34	4.84	13.72	13.83	7.39	8.39	9.22	6.69	5.10	7.1	7.1
30-40	7.08	7.88	8.50	6.63	5.40	13.52	13.70	7.46	8.29	8.95	6.99	5.69	7.1	7.0
40-50	6.30	6.89	7.33	6.07	5.20	12.40	12.67	6.62	7.24	7.70	6.38	5.46	6.3	6.3
50-60	4.85	5.18	5.39	4.84	4.39	10.61	10.97	5.07	5.41	5.63	5.07	4.61	4.8	4.7
60-70	4.08	4.30	4.42	4.16	3.89	9.48	9.93	4.26	4.48	4.60	4.35	4.06	4.1	4.0
70-80	3.60	3.76	3.81	3.72	3.54	8.66	9.19	3.74	3.90	3.95	3.88	3.69	3.6	3.6
80-90	3.26	3.37	3.38	3.40	3.27	7.99	8.60	3.38	3.48	3.48	3.53	3.40	3.2	3.2
90-100	3.00	3.07	3.05	3.14	3.05	7.41	8.11	3.09	3.16	3.12	3.25	3.16	3.0	2.9
100-110	2.79	2.83	2.78	2.93	2.86	6.91	7.68	2.86	2.90	2.84	2.99	2.96	2.7	2.8
110-120	2.61	2.62	2.56	2.74	2.70	6.46	7.31	2.67	2.68	2.60	2.85	2.78	2.6	2.6
120-130	2.45	2.45	2.37	2.58	2.55	6.05	6.97	2.49	2.49	2.40	2.64	2.62	2.5	2.4
130-140	2.31	2.29	2.20	2.43	2.42	5.68	6.66	2.34	2.32	2.22	2.48	2.47	2.3	2.3
140-150	2.19	2.16	2.06	2.30	2.29	5.34	6.38	2.21	2.18	2.06	2.34	2.34	2.2	2.2
150-160	2.08	2.03	1.93	2.17	2.18	5.03	6.12	2.08	2.04	1.93	2.20	2.21	2.0	2.0
160-170	1.98	1.92	1.81	2.06	2.07	4.74	5.88	1.97	1.92	1.80	2.08	2.10	2.0	2.0
170-180	1.88	1.81	1.71	1.95	1.97	4.47	5.66	1.86	1.80	1.69	1.96	1.99	1.8	1.9
180-210	4.92	4.67	4.38	5.06	5.19	11.49	15.41	4.78	4.57	4.24	5.02	5.17	4.9	4.8
210-240	4.31	4.01	3.75	4.38	4.55	9.84	14.06	4.09	3.87	3.57	4.28	4.48	4.2	4.1
240-270	3.79	3.46	3.29	3.80	4.01	8.43	12.90	3.50	3.26	3.00	3.64	3.89	3.7	3.7
270-300	3.55	2.99	2.79	3.30	3.54	7.24	11.90	3.00	2.75	2.53	3.10	3.37	3.2	3.3
300-330	2.96	2.59	2.41	2.87	3.12	6.21	11.04	2.56	2.32	2.12	2.63	2.93	2.8	2.8
330-360	2.63	2.24	2.09	2.49	2.76	5.31	10.28	2.18	1.94	1.77	2.23	2.53	2.4	2.5

[a] Models 229 and 230 represent the mean of 20 calculations.

VITA

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