EVALUATION OF THE GROUND-WATER RESOURCES OF PARTS OF LANCASTER AND BERKS COUNTIES, PENNSYLVANIA

By James M. Gerhart and George J. Lazorchick

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FACTORS FOR CONVERTING INCH-POUND UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI)

Multiply inch-pound unit	By	To obtain SI unit
	Length	
inch	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi2)	2.590	square kilometer (km2)
acre	4047	square meter (m2)
	Flow	
million gallon (Mgal)	3785	cubic meter (m3)
gallon per day (gal/d)	0.003785	cubic meter per day (m3/d)
million gallon per day (Mgal/d)	0.04381	cubic meter per second (m3/s)
cubic foot per second (ft3/s)	0.02832	cubic meter per second (m3/s)
inch per year (in/yr)	25.40	millimeter per year (mm/yr)
million gallon per day per square mile [(Mgal/d)/mi2]	0.01691	cubic meter per second per square kilometer [(m3/s)/km2]
	Specific capacity	
gallon per minute per foot [(gal/min)/ft]	0.000207	cubic meter per second per meter [(m3/s)/m]
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Stream leakage coefficient	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)

EVALUATION OF THE GROUND-WATER RESOURCES OF PARTS OF LANCASTER AND BERKS COUNTIES, PENNSYLVANIA

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ABSTRACT

Secondary openings in bedrock are the avenues for virtually all ground-water flow in a 626-square-mile area in Lancaster and Berks Counties, Pennsylvania. The number, size, and interconnection of secondary openings are functions of lithology, depth, and topography. Ground water actively circulates to depths of 150 to 300 feet below land surface. Total average annual ground-water recharge for the area is 388 million gallons per day, most of which discharges to streams from local, unconfined flow systems.

A digital ground-water flow model was developed to simulate unconfined flow under several different recharge and withdrawal scenarios. On the basis of lithologic and hydrologic differences, the modeled area was sub-divided into 22 hydrogeologic units. A finite-difference grid with rectangular blocks, each 2,015 by 2,332 feet, was used. The model was calibrated under steady-state and transient conditions. The steady-state calibration was used to determine hydraulic conductivities and stream leakage coefficients and the transient calibration was used to determine specific yields.

The 22 hydrogeologic units fall into four general lithologies: Carbonate rocks, metamorphic rocks, Paleozoic sedimentary rocks, and Triassic sedimentary rocks. Average hydraulic conductivity ranges from about 8.8 feet per day in carbonate units to about 0.5 feet per day in metamorphic units. The Stonehenge Formation (limestone) has the greatest average hydraulic conductivity--85.2 feet per day. Average gaining-stream leakage coefficient ranges from about 1.83 feet per day in carbonate units to about 0.11 feet per day in Paleozoic sedimentary units. The Richland Formation (limestone, dolomite) has the greatest gaining-stream leakage coefficient--16.81 feet per day. Specific yield ranges from 0.06 to 0.09 in carbonate units, and is 0.02, 0.015, and 0.012 in metamorphic, Paleozoic sedimentary, and Triassic sedimentary units, respectively.

Transient simulations were made to determine the effects of four different combinations of natural and artificial stresses. Natural aquifer conditions (no ground-water withdrawals) and actual aquifer conditions (current ground-water withdrawals) were simulated for two years under normal seasonal and hypothetical drought (60-percent reduction in winter-spring recharge) conditions.

In October, 6 months after the hypothetical drought, simulated declines in water-table altitude due to the drought occurred everywhere and ranged from a median of 3.6 feet in carbonate units to 8.7 feet in noncarbonate units. Simulated base flows for five major streams were reduced by 33 to 51 percent during the hypothetical drought.

Also in October, maximum simulated declines in water-table altitude due to ground-water withdrawals ranged from 33 feet in carbonate units to 79 feet in Triassic sedimentary units. Simulated base flows for five major streams were reduced by the amount of ground water withdrawn.

Finally, again in October, maximum simulated declines in water-table altitude due to the combination of hypothetical drought and ground-water withdrawals ranged from 38 feet in carbonate units to 109 feet in Triassic sedimentary units. Due to aquifer dewatering, simulated declines were as much as 24 feet greater than the sum of the separate simulated declines that were caused by hypothetical drought and ground-water withdrawals. Some of the greatest simulated declines were in well fields operated by three municipalities that experienced water-supply problems during the 1980-81 drought.

INTRODUCTION

Background

In 1979, the U.S. Geological Survey and the Susquehanna River Basin Commmission began an evaluation of the ground-water resources of the lower Susquehanna River basin. The lower basin is in south-central and southeastern Pennsylvania and north-central and northeastern Maryland and occupies all or parts of 13 counties. The lower basin is primarily rural and ground water from wells and springs is an important source for municipal, industrial, agricultural, and domestic water use. Furthermore, many surface-water supplies are sustained, especially in dry periods, by ground-water discharge. Projected population growth in the Lancaster-York-Harrisburg area will lead to heavier demands on the ground-water resources of the lower basin.

The lower Susquehanna River basin investigation consists of two parts. The first part is an evaluation of the ground-water resources of the lower basin through the use of a regional ground-water flow model (Gerhart and Lazorchick, 1984). The second part involves a more detailed model of the most developed area in the lower basin--an area in Lancaster and Berks Counties that is underlain largely by carbonate rocks. The more detailed model, which is presented in this report, is intended to provide a technical basis for addressing current and future ground-water supply problems.

Purpose and Scope

The overall purpose of this report is to characterize the ground-water resources of a 626-mi^2 area in Lancaster and Berks Counties by compiling available ground-water resource data in the form of a digital ground-water flow model. Specific objectives necessary to the characterization process include (1) determination of the geometry and hydrologic characteristics of the various aquifers; (2) determination of the ground-water--surface-water relations for each aquifer; (3) quantification of the natural sources and discharges for each aquifer; and (4) estimation of the impacts of several different climatic conditions and ground-water withdrawal scenarios on the ground-water flow system.

Modeled Area

The modeled area is that part of the lower Susquehanna River basin in central and northern Lancaster County and southwestern Berks County that is underlain largely by carbonate rocks (fig. 1). The area covers 626 mi2 and is bounded on the west by the Susquehanna River and on the east by the basin boundary and noncarbonate rocks. The northern and southern limits of the modeled area coincide with contacts between carbonate and noncarbonate rocks. The largest population center is Lancaster; smaller population centers include East Petersburg, Ephrata, Landisville, Lititz, Manheim, Marietta, Millersville, Morgantown, Mt. Joy, New Holland, Quarryville, Strasburg, and Terre Hill.

The carbonate rocks, which account for 70 percent of the modeled area, were selected for this more detailed model evaluation because of their known aquifer potential and relatively heavy current and projected use of ground water. However, several areas that contain noncarbonate rocks also were included. Triassic sedimentary rocks of the upper Conestoga River basin (a subbasin of the lower basin) were included to augment hydrogeologic data for a U.S. Geologic Survey ground-water contamination study currently in progress there. Shales of the Cocalico Formation in the northern part of the modeled area were included because their hydrogeology has not been previously studied. A small area of metamorphic rocks of the Wissahickon Formation was included to facilitate selection of model boundary conditions. Metamorphic rocks in parts of the Antietam, Harpers, and Chickies Formations were included because of their presence within the boundaries of the carbonate rock area. For the same reason, diabase sills within Triassic sedimentary rocks also were included.

Method of Investigation and Sources of Data

A three-dimensional ground-water flow model documented in Trescott (1975) and revised by Trescott and Larson (1976) was modified for use in the evaluation of the ground-water resources of the entire lower basin (Gerhart and Lazorchick, 1984). The modified model, with only minor additions, was used in this investigation to simulate two-dimensional ground-water flow in a single-layer aquifer; the model was calibrated under steady-state and transient conditions. After calibration, it was used to estimate the effects of natural and artificial stresses on the ground-water flow system.

Available hydrogeologic data were incorporated in the model. The most important sources of data were the inventory of water wells maintained by the U.S. Geological Survey, and the file of well drillers' reports maintained by the Pennsylvania Geological Survey. Data such as water levels, specific capacities, well depths, and water-bearing zone depths were compiled. Other data used in the study include precipitation data published by the National Oceanic and Atmospheric Administration (NOAA), aquifer-test data from U.S. Geological Survey files and various published hydrologic investigations, and streamflow data collected at U.S. Geological Survey gaging stations. Data on ground-water use were obtained from the Division of Comprehensive Resources, Bureau of Resources Programming, Pennsylvania Department of Environmental Resources. Water levels measured in 68 wells in October 1980 and April 1981 were used for transient-model calibration.

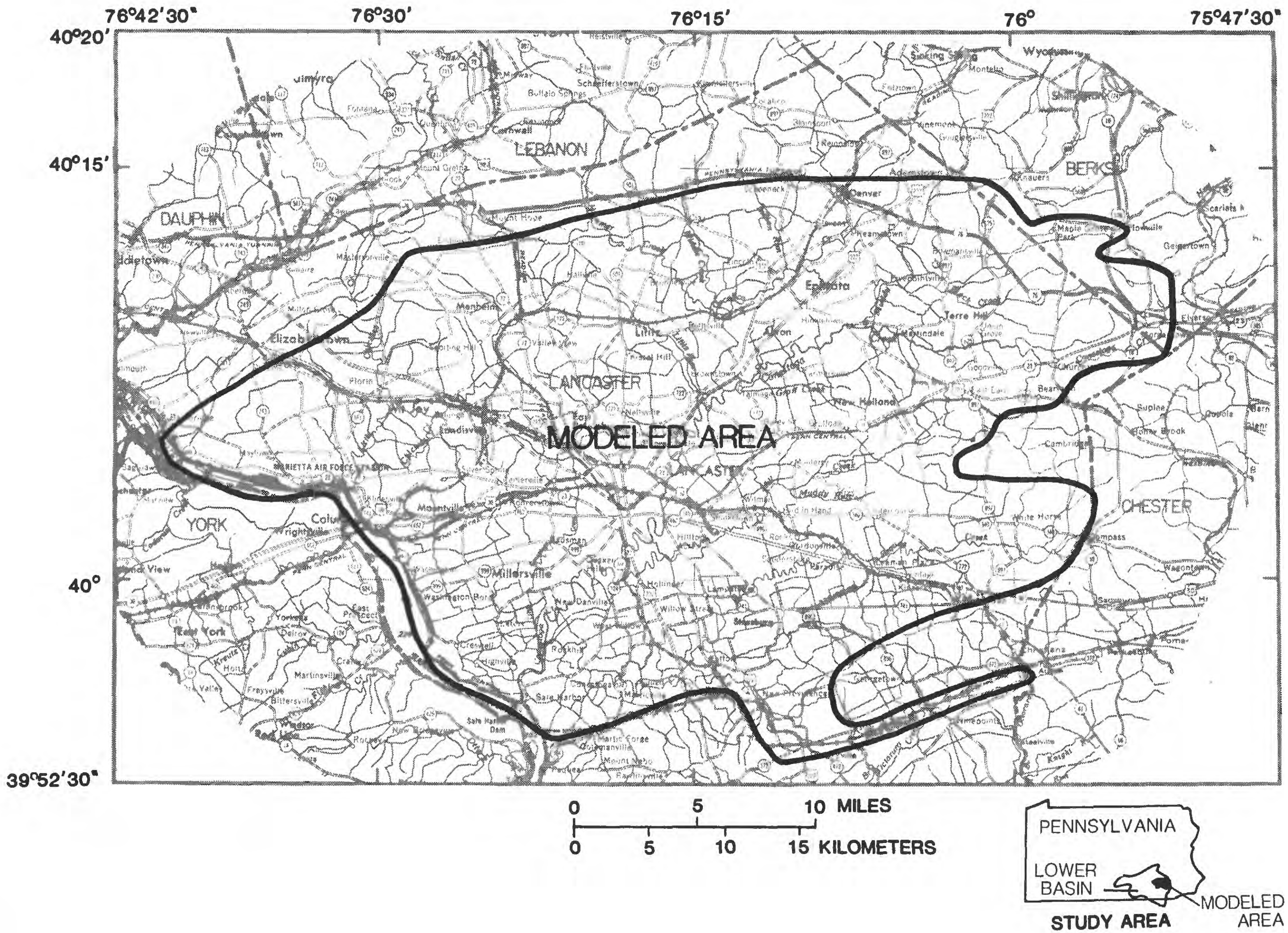


Figure 1.--Location of modeled area.

Previous Investigations

The ground-water resources of the area have been the subject of several hydrogeologic investigations. The New Oxford Formation in Lancaster County was studied by Johnston (1966). The hydrogeology of the carbonate rocks in the Lancaster 15-minute quadrangle was described by Meisler and Becher (1966, 1971). Poth (1977) summarized the ground-water resources of Lancaster County. The ground-water resources of the Gettysburg and Hammer Creek Formations. including parts of Lancaster and Berks Counties, were described by Wood (1981). Gerhart and Lazorchick (1984) presented a model used for a regional ground-water resource evaluation of the lower Susquehanna River basin, which included the area in this study.

Acknowledgments

The assistance of Susquehanna River Basin Commission personnel in many phases of the investigation is appreciated. The authors also wish to thank S. P. Larson for his help in modifying the numerical model program, and J.V. Tracy for his suggestions concerning the use of the head-dependent stream leakage option and model-calibration procedure. A. E. Becher and J. H. Williams are acknowledged for their helpful suggestions pertaining to the approach to the problem. The authors wish to thank L. E. Taylor, Pennsylvania Geological Survey, for making drillers' records available, and W. A. Gast, Division of Comprehensive Resources, Bureau of Resources Programming, Pennsylvania Department of Environmental Resources, for computer-sorting data from drillers' records. Finally, the authors acknowledge S. Runkle, also of the Division of Comprehensive Resources, for making ground-water use data available.

PHYSICAL SETTING

Physiography

The modeled area is located in the Piedmont physiographic province and includes parts of three physiographic subdivisions (fig. 2). Most of the area is in the Conestoga Valley, which is characterized by rolling lowlands. The northeastern corner of the area is in the Triassic Lowland and is characterized by broad highlands and ridges. The southwestern corner of the area is in the Piedmont Upland, which is characterized by rugged, dissected highlands. The highest elevation is about 1,050 ft above sea level in the Triassic Lowland and the lowest is about 170 ft above sea level along the Susquehanna River in the Piedmont Upland.

The Susquehanna River drains the area. Chickies Creek, Conestoga River, and Pequea Creek are the main tributaries to the Susquehanna River in the area. Tributaries to these three streams include Little Chickies, Little Conestoga, Hammer, Middle, Cocalico, Muddy, Mill, and Beaver Creeks.

Climate

The average annual temperature (1941-70) at the NOAA weather station in Ephrata is about 53°F. The average annual precipitation for the same period ranges from about 38 inches near the Susquehanna River to about 42 inches in

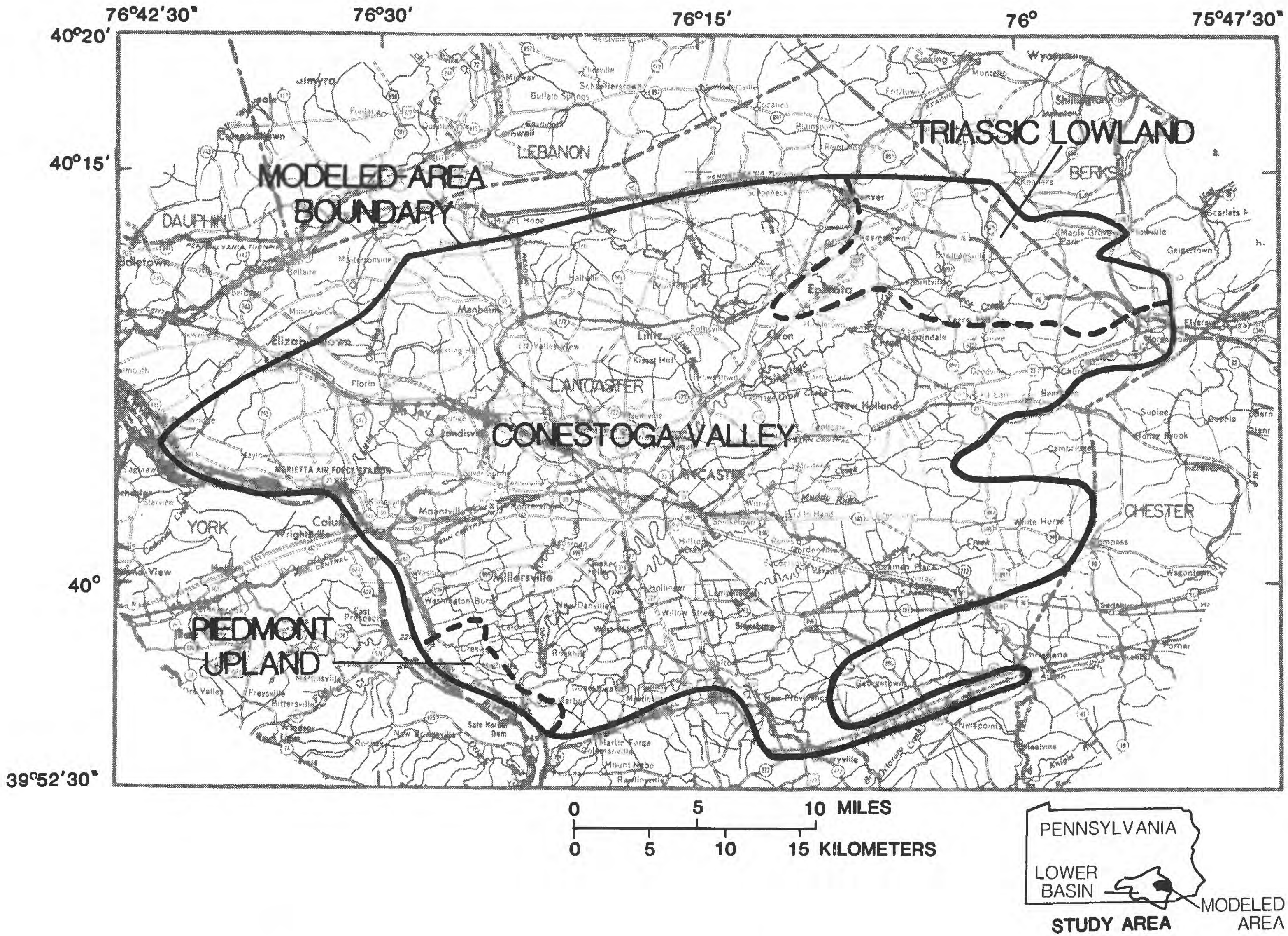


Figure 2.--Physiographic subdivisions of the Piedmont province in modeled area.

the eastern part of the area (fig. 3). Precipitation varies seasonally, with about one-third of the average annual total occurring in June, July, and August. The areal distribution of precipitation is fairly uniform during the winter, but varies considerably during the summer because of thunderstorms.

GEOLOGY

The three major categories of rocks are found in the modeled area. Igneous rocks (diabase) are found in the Triassic Lowland. Clastic rocks (shale, siltstone, sandstone, and conglomerate) and carbonate rocks (limestone and dolomite) are found in the Triassic Lowland and Conestoga Valley. Metamorphic rocks (schist and quartzite) are found in the Conestoga Valley and Piedmont Upland. A geologic map of Pennsylvania, published by the Pennsylvania Geological Survey in 1980, gives detailed descriptions of the lithologies in each physiographic subdivision, as well as their areal distributions.

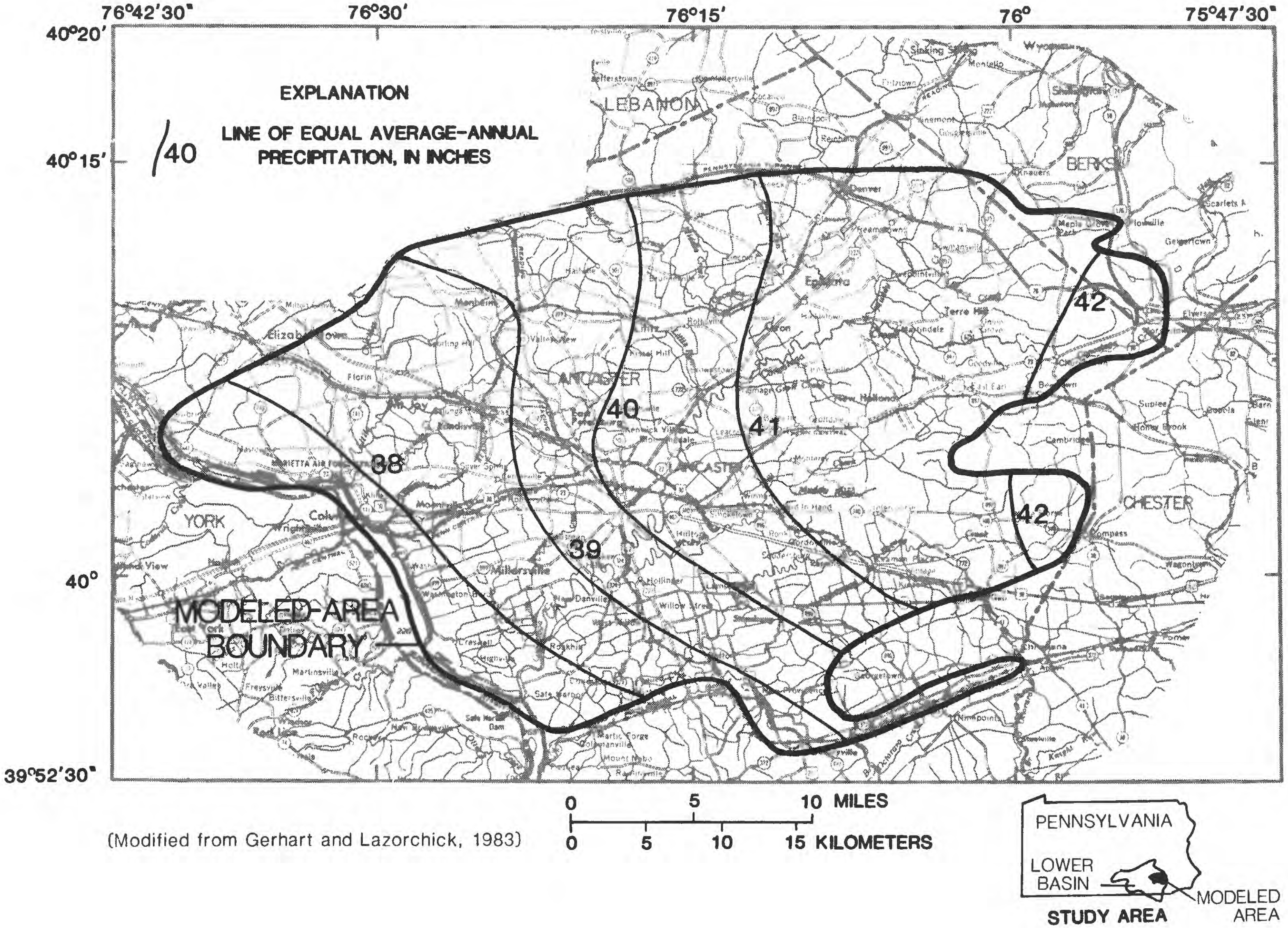
The rocks in the Conestoga Valley are Cambrian and Ordovician in age; the rocks in the Triassic Lowland are predominantly Triassic in age (some diabase is Jurassic). The age of many of the rocks in the Piedmont Upland is uncertain, but probably is Cambrian or Ordovician. The age of the Conestoga Formation also is uncertain, but probably is Lower Ordovician. The Conestoga Formation lies unconformably on Lower Cambrian rocks.

Due to metamorphism, the rocks in the Piedmont Upland are not easily correlated. However, in the Conestoga Valley and Triassic Lowland, individual formations have been recognized and mapped. The stratigraphy and estimated thicknesses of these formations are shown in table 1. The vertical spacing of the horizontal lines separating the formations is not indicative of their relative thicknesses. Within formations, the actual thicknesses may differ because of shifting depositional environments and differential erosion.

In general, the stratigraphic thickness of the Cambrian and Ordovician sequences increases eastward and the stratigraphic thickness of the Triassic sequence increases westward. The thickness of the Cambrian sequence averages about 10,000 ft and that of the Ordovician sequence averages about 6,500 ft. The thickness of the Triassic sequence averages about 14,000 ft. Diabase dikes of different thickness and length intrude the Triassic sedimentary rocks.

GROUND-WATER HYDROLOGY

The geologic framework of the ground-water flow system consists of bedrock overlain by a mantle of weathered bedrock. The thickness of the weathered mantle is largely a function of topography. It generally is thickest on hilltops and slopes, and thinnest in draws and valleys where erosion by surface water is greatest. In addition, it is commonly thick along the flanks of major ridges because of mass wasting and slumping. The weathered mantle includes all the material from soil at land surface to unconsolidated rock fragments just above bedrock.



(Modified from Gerhart and Lazorchick, 1983)

Figure 3 --Average annual precipitation in modeled area.

Table 1.--Cambrian, Ordovician, and Triassic stratigraphy in modeled area.

[Compiled from Johnston, 1966; MacLachlan and Root, 1966; Meisler and Becher, 1971; Pennsylvania Topographic and Geological Survey, 1980; and Wood, 1981. Numbers in parentheses are estimated formation thicknesses, in feet.]

Cambrian

Conococheague Group	Millbach Formation (1,200-2,000)
	Snitz Creek Formation (300-400)
Buffalo Springs Formation (1,500-3,800)	
Zooks Creek Formation (1,600)	
Ledger Formation (1,000)	
Kinzers Formation (300-600)	
Vintage Formation (350-550)	
Antietam Formation (100-200)	
Harpers Formation (800-1,000)	
Chickies Formation (400-900)	

Ordovician

Cocalico Formation (?)	
Hershey Formation (200) Myerstown Formation (200) Annville Formation (200)	
Beekmantown Group	Ontelaunee Formation (<600)
	Epler Formation (2,000-2,500)
	Stonehenge Formation (500-1,000)
Conestoga Formation - probably Middle Cambrian to Lower Ordovician (?)	

Triassic

Hammer Creek Formation (9,400-12,200)	
New Oxford Formation (500-4,800)	Stockton Formation (2,300-6,000)

The weathered mantle is relatively porous and permeable and, because of its ability to accept precipitation, acts as a source of recharge to the bedrock below. Where the weathered mantle is saturated, ground water occupies the spaces between soil particles and rock fragments. The bedrock, on the other hand, has very low primary porosity and is less permeable than the weathered mantle. Ground water is found in the bedrock only because of the presence and development of secondary openings. Primary openings such as spaces between rock grains are either virtually nonexistent or of minor importance because of compaction and cementation. Secondary openings are caused by tectonic stresses and include openings along bedding planes, cleavage planes, joints, and faults. Commonly, these openings are enlarged by weathering processes and solution.

The number and size of the openings determine the secondary porosity of the bedrock; the degree to which the openings are interconnected determines its secondary permeability. The number, size, and interconnection of the secondary openings differ with lithology, depth below land surface, and topographic setting. Secondary porosity and permeability decrease with depth due to the increase in pressure and the decrease in weathering and solution. Also, secondary porosity and permeability are relatively low under hilltops and relatively high under draws and valley.

Ground water in the weathered mantle is under unconfined conditions. In contrast, ground water in the secondary openings in bedrock commonly is under confined conditions due to the essentially impermeable bedrock on the sides of the openings. However, because there are no well-defined, continuous confining beds, and because the degree of hydraulic connection between the weathered mantle and the secondary openings in the underlying bedrock is generally high, the entire ground-water flow system is considered as one complex unconfined aquifer.

The water table generally is a subdued replica of the land surface. It is deepest under hilltops and nearest land surface in draws and valley. It commonly is in the lower part of the weathered mantle but it can also be in the bedrock, especially under hilltops. Streams generally are hydraulically connected to the water table; however, some stream reaches may be perched.

The flow system is recharged by precipitation that infiltrates the weathered mantle and percolates to the water table. Stream valleys are the discharge locations for ground water. Local flow systems dominate, with ground water discharging in stream valleys adjacent to its areas of recharge. Between areas of recharge and discharge, ground water flows in directions of decreasing potential, or from high to low water-table altitudes. Where the water table is above the bedrock, ground water may reach its discharge location without leaving the weathered mantle. Alternately, ground water may enter the bedrock and follow shallow or deep flow paths through connected secondary openings until it is discharged. Not all the ground water that discharges into stream valleys reaches streams; a minor amount will be lost to evapotranspiration where the water table is near the land surface.

DIGITAL MODEL OF GROUND-WATER FLOW SYSTEM

Conceptual Model

The conceptual model used in this investigation (fig. 4) is virtually identical to the conceptual model used in the lower-basin evaluation (Gerhart and Lazorchick, 1984). For the same reasons discussed in that report, it was assumed that porous-media methods of analysis could be used in this investigation. Those reasons were the large scale of the analysis, the apparent degree of interconnection of secondary openings, and the qualitative correlation between features of the modeled-area ground-water flow system and the features of a similar but theoretical flow system in an idealized medium (Toth, 1963, fig. 2a). As a result, conventional, porous-media, ground-water flow modeling was used to analyze the ground-water flow system.

As shown in figure 4, the ground-water flow system was conceptualized as an unconfined aquifer consisting of bedrock overlain by a relatively thin weathered mantle. The general characteristics shown in the diagram are present throughout the area and are the major influences on the flow of ground water. The characteristics represent a summary of the results of previous hydrogeologic investigations.

Although the general features of the conceptual model are observed throughout the area, specific characteristics differ with lithology. For example, all lithologies are recharged by infiltration of precipitation, but one lithologic unit may accept recharge at twice the rate of another. Lithologies that have high secondary porosity and permeability tend to have deeper ground-water circulation, deeper water tables, less seasonal water-table fluctuation, and greater amounts of recharge (and discharge). Because of their solubility, the carbonate rocks are apt to have higher secondary porosity and permeability; conversely, the igneous and well-cemented sedimentary and metamorphic rocks are likely to have lower secondary porosity and permeability.

Simplified Conceptual Model

As seen in the conceptual model, secondary porosity and permeability differ with depth below land surface and topography. These differences, which are continuous and gradational, were replaced by incremental differences in the simplified conceptual model. The decrease in secondary porosity and permeability with depth was approximated by a single layer whose upper limit is the land surface and whose lower limit is the base of the zone of active ground-water circulation (fig. 5). This layer includes the weathered mantle and the upper part of the bedrock. Ground water below this layer is not stagnant, but data on water-bearing zones in wells indicate a marked reduction in secondary permeability. The results of the lower-basin evaluation (Gerhart and Lazorchick, 1984), in which this lower part of the system was modeled as an active layer, indicate that less than 8 percent of the total ground-water flow occurs in this deeper layer. Therefore, in this investigation, ground-water flow below the base of active ground-water circulation was considered negligible and modeling it was not warranted.

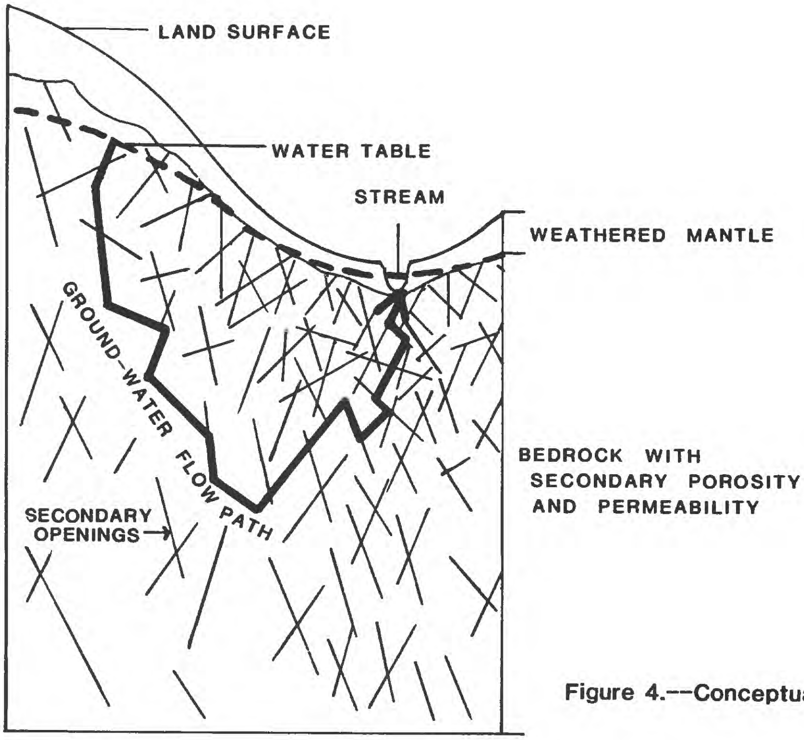


Figure 4.--Conceptual model of ground-water flow.

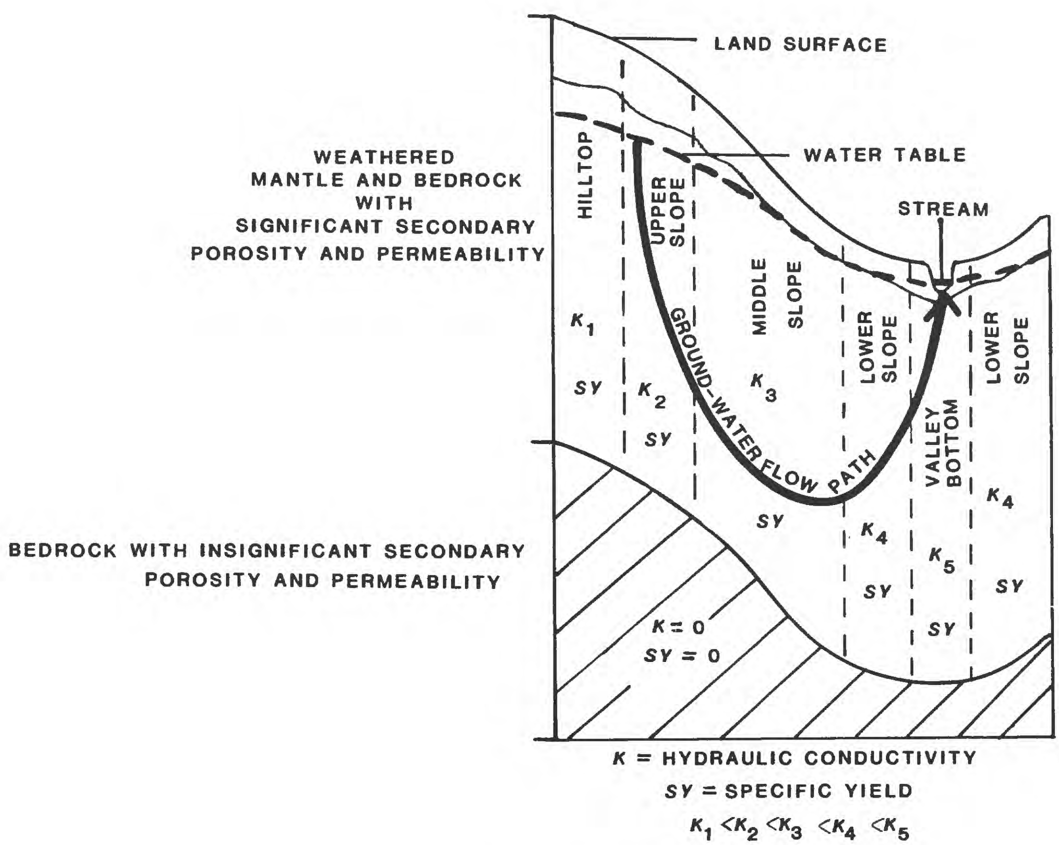


Figure 5.--Simplified conceptual model of ground-water flow.

The decrease in secondary permeability from valley bottom to hilltop was approximated by five topographic settings (fig. 5). Hydraulic conductivity is a function of secondary permeability, and therefore, is greatest under valley bottoms and least under hilltops. Specific yield was assumed to be uniform for all topographic settings because of a lack of data to the contrary.

All ground water discharges into streams in the simplified conceptual model. Because the water table generally is below the root zone of most vegetation and because data needed to determine the magnitude and distribution of evapotranspiration were not available, ground-water evapotranspiration was not included in the model. The effect on model results of not simulating ground-water evapotranspiration is overestimation of the effects of stress. In reality, when the ground-water flow system is stressed, evapotranspiration decreases, which helps balance the stress. The decrease in evapotranspiration offsets some of the water-table decline and base-flow reduction that would occur if the capture of evapotranspiration were not a possibility. Such capture is not possible in the model, so slightly exaggerated water-table declines and base-flow reductions will result. Overestimation of such effects provides a cushion for the evaluation of the ground-water resources.

As stated in the discussion of the conceptual model, secondary porosity and permeability are influenced by lithology as well as by depth and topography; these factors cause differences in hydrologic characteristics among lithologies. The differences in lithology were approximated by dividing the area into 22 hydrogeologic units. Table 2 identifies the geologic formations in the 22 units and plate 1 shows the unit locations, geologic formations, and lithologies. The unit boundaries follow the edges of model grid blocks. The division of the area into 22 units permitted the assignment, by unit, of aquifer thickness, hydraulic conductivity, stream leakage coefficient, specific yield, depth to water table, and model recharge.

Of the 22 units, four (15, 16, 17, 22) are transitional units. They were included to better approximate the areal distribution of units where many grid blocks along a contact between two lithologies contain approximately equal parts of each lithology. All but two units were grouped into one of four general lithologies (table 2), which will be used for purposes of comparison throughout the report. Thirteen units contain only carbonate rocks (1-11, 16, 17), four contain only Triassic sedimentary rocks (18,19,21,22), two contain metamorphic rocks (12,14), and one contains Paleozoic sedimentary rocks (13). One unit (15) contains both carbonate and metamorphic rocks. Diabase (unit 20), although not modeled in the lower-basin evaluation (Gerhart and Lazorchick, 1984), was included as an active unit in this investigation because of the finer scale of analysis.

As the final step in the simplification of the conceptual model, aquifer thickness was determined from data on water-bearing zones in drilled wells. These data were obtained from Pennsylvania Geological Survey drillers' records. For each hydrogeologic unit, the depth below land surface at which a significant reduction in the number of water-bearing zones occurs was taken to be the base of active ground-water circulation and, therefore, the thickness of the aquifer. For all but four units, that thickness is 300 ft. In the Cocalico Formation (unit 13), the aquifer is only 150 ft thick, and in the

Table 2.--Hydrogeologic subdivision used in model

[General lithologies: C, carbonate rocks; M, metamorphic rocks; PS, Paleozoic sedimentary rocks; TS Triassic sedimentary rocks.]

Hydro-geologic unit	General lithology	Area, in square miles	Geologic formations
1	C	19.9	Stonehenge
2	C	69.1	Ledger
3	C	124.2	Conestoga
4	C	57.3	Epler, Annville, Hershey, Myerstown
5	C	20.6	Vintage
6	C	47.5	Buffalo Spring, Snitz Creek
7	C	15.0	Millbach
8	C	43.3	Zooks Corner
9	C	2.4	Richland
10	C	5.9	Ontelaunee
11	C	3.9	Kinzers
12	M	36.2	Antietam, Harpers, Chickies
13	PS	60.5	Cocalico
14	M	9.6	Wissahickon
15		18.4	Combination of units 3, 12
16	C	13.5	Combination of units 5, 11
17	C	12.3	Combination of units 1, 6-11
18	TS	32.9	Hammer Creek
19	TS	5.6	Hammer Creek Conglomerate
20		8.3	Diabase
21	TS	10.8	New Oxford, Stockton
22	TS	8.6	Combination of units 18, 19

Wissahickon Formation (unit 14), the New Oxford and Stockton Formations (unit 21), and diabase (unit 20), the aquifer is 250 ft thick. Saturated aquifer thickness is less than these total aquifer thicknesses.

Discretization

The simplified conceptual model was further reduced to obtain a digital-model representation which is amenable to finite-difference methods. A grid consisting of 68 rows and 100 columns of rectangular blocks was superimposed on the area. Each grid block is 2,015 by 2,332 ft and can be referred to by its row and column numbers, respectively--for example, block 36-26. The rows of the grid were oriented parallel to the east-west direction (plate 1).

The schematic diagram in figure 6 shows how this grid further reduces the features of the simplified conceptual model. For example, the middle-slope topographic setting in figure 5 has been divided into four middle-slope grid blocks, each with the same hydraulic conductivity and aquifer thickness.

Model Program

The ground-water flow model used in this investigation is a modified version of the three-dimensional finite-difference model of Trescott (1975) and Trescott and Larson (1976). The model program is listed in attachment A and instructions for its use are given in attachment B. It is essentially the same model that was used in the lower-basin evaluation (Gerhart and Lazorchick, 1984), with the addition of several input-output modifications. It was used in a two-dimensional mode to simulate unconfined ground-water flow in a single layer, with saturated thickness recalculated every iteration. Simulations made during this investigation were run on an IBM 3033[1/] computer at the Applied Physics Laboratory, Johns Hopkins University.

CALIBRATION OF MODEL UNDER AVERAGE ANNUAL STEADY-STATE CONDITIONS

General Procedure

The purpose of the steady-state calibration was to determine the distribution and magnitude of hydraulic conductivity and stream leakage coefficients. Simply stated, this calibration consisted of routing ground-water recharge to streams under a particular water-table configuration. Many combinations of hydraulic conductivity and stream leakage coefficients could produce an acceptable routing; a combination supported by hydrologic data was used. The model was calibrated under average annual steady-state conditions because there is never a particular time when all parts of the area are at steady state. However, over the course of an average year or many years, there is little or no net gain or loss of ground water from aquifer storage; therefore, it was assumed that an average annual approach could be used.

1/ Use of brand names in this report is for indentification purposes only and does not constitute endorsement by the U.S. Geological Survey.

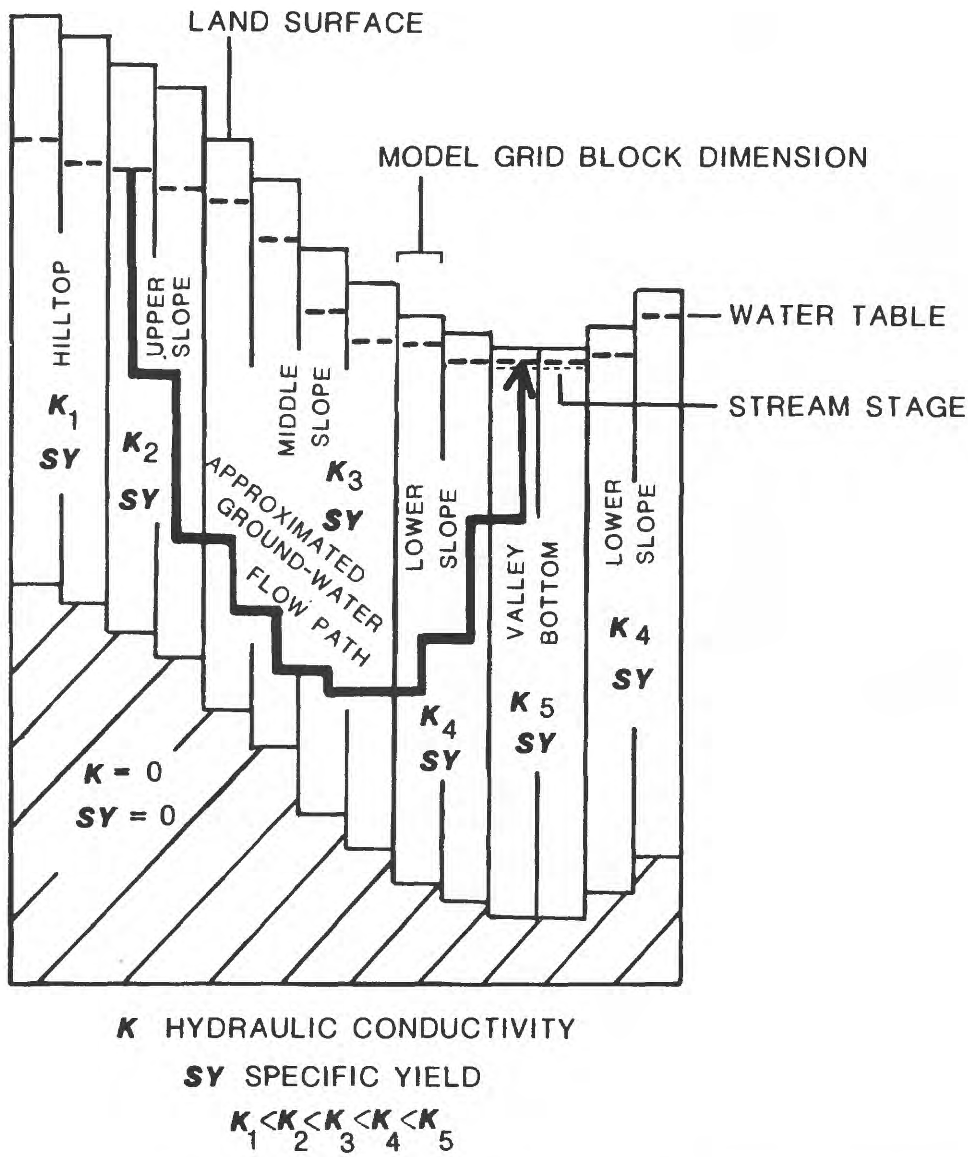


Figure 6.--Digital-model representation of simplified conceptual model.

There were relatively few large, consumptive, ground-water withdrawals in the modeled area and they were not well documented in terms of rates of withdrawal and water-table decline. Therefore, no withdrawals were included in the steady-state calibration. This was considered reasonable because nearly all the water-table altitude data used to calibrate the model consisted of static water-level measurements in sporadically-pumped domestic wells away from sites of major withdrawals.

Model-generated water-table altitudes were statistically compared to estimated water-table altitudes during calibration. Also, as a further check, model-generated base flows for six streams were compared to estimated base flows obtained by graphical separation of streamflow hydrographs. Initial estimates of hydraulic conductivity and stream leakage coefficients for each hydrogeologic unit were adjusted during calibration. Aquifer thicknesses, model recharge, and boundary conditions were not adjusted.

Ground-Water Conditions

The average land-surface altitude for each grid block was estimated by overlaying a small template on each model grid block on 7 1/2-minute quadrangle maps. The land-surface altitudes at 6 equally-spaced points on the template were averaged to obtain the average land-surface altitude for each block.

The dominant topographic setting of each grid block was subjectively assigned by examining the topography within each block and its relation to the surrounding blocks. Again, 7 1/2-minute quadrangle maps were used. Each block was assigned a topographic setting of either hilltop, upper-slope, middle-slope, lower-slope, or valley-bottom (the five settings shown in the simplified conceptual model in figure 5). The distribution of these settings is generalized in figure 7. About 72 percent of the modeled area is middle slope setting. Upper-slope blocks make up about 9 percent of the area and generally occur along prominent ridges and in highlands. Lower-slope blocks occur along major stream valleys and comprise about 16 percent of the area. Very few blocks have dominant topographic settings of hilltop (1 percent) or valley-bottom (2 percent).

Water-level measurements were available for 746 wells in the area. One of the five topographic settings was assigned to each well. Measured depths to water (below land surface) were analyzed, grouping them by hydrogeologic unit and topographic setting. These depth measurements were made during different seasons and different years in different parts of the area. It was assumed that the large number of measurements would statistically overwhelm any seasonal or long-term bias in a particular area. It also was assumed that there was no bias due to different well depths or artificial stresses.

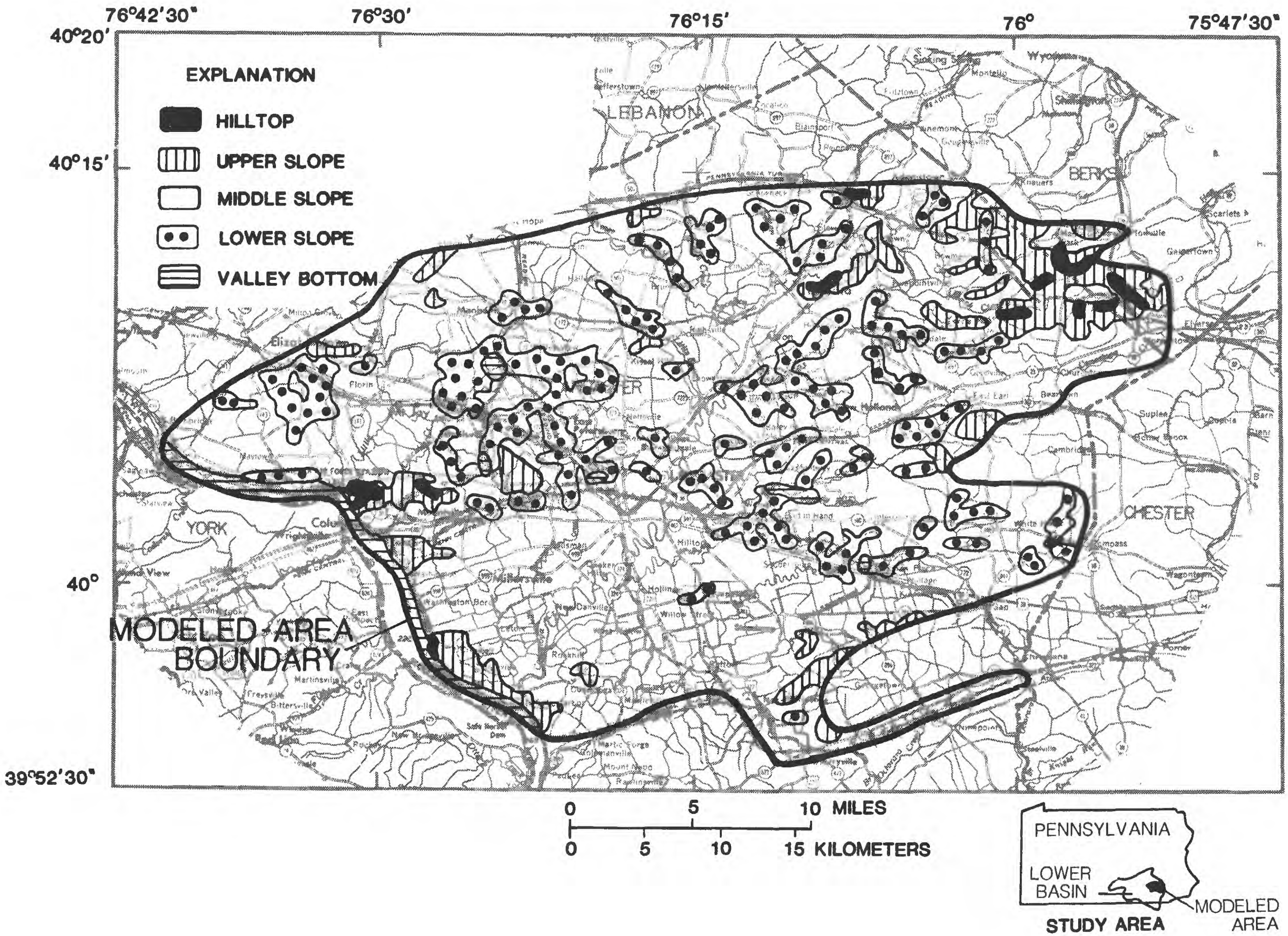


Figure 7.--Generalized topography in modeled area.

The median depths to water for the five topographic settings in each hydrogeologic unit are shown in table 3. Units with insufficient data were assigned depths to water that correspond to those of units of similar lithology and physiography. For all units, the depth to water increases from valley-bottom to hilltop settings. The difference in medians among units is probably related to lithology and local relief.

By using the average land-surface altitude, the dominant topographic setting, and the median depths to water in table 3, the average annual water-table altitude was calculated for each grid block. This will be referred to as the estimated water-table altitude. Where the estimated water-table altitude was below the estimated stream altitude, it was set equal to the stream altitude because there is no evidence of perennially losing streams in the area. A generalized water-table map of the area is shown in figure 8. During steady-state calibration, the model-generated water-table altitudes were compared to these estimates.

Surface-Water Conditions

Average annual surface-water conditions were assumed to be represented on 7 1/2-minute quadrangle maps. Streams indicated as being perennial were considered to be the discharge locations for the ground-water flow system. Lakes larger than 0.002 mi^2 (1.3 acres) also were included.

About 55 percent of the grid blocks contain at least one stream segment or lake. Average surface-water altitudes were estimated from land-surface contours on 7 1/2-minute quadrangle maps. The surface-water altitude for each block was calculated by averaging stream segment and lake altitudes, weighted by their surface areas. For those stream segments represented by single lines on the maps, a width of 15 ft was used in conjunction with stream segment length to obtain the surface area. For those blocks located partly in the Susquehanna River, and upstream from hydropower dams, pool altitudes were used to estimate the surface-water altitude. Blocks entirely in the Susquehanna River were treated differently and are discussed in the section on boundary conditions.

Recharge

Virtually all recharge to the unconfined aquifer is derived from precipitation that infiltrates the weathered mantle and percolates to the water table. It occurs everywhere, except possibly in the immediate vicinity of streams. Because the model grid blocks are fairly large, at least some recharge occurs in every block.

Recharge is a function of amount and intensity of precipitation, lithology, topography, soil moisture, soil type, and temperature, among other factors. For the steady-state calibration, it was assumed that model recharge depends only on lithology (with its associated soil type) and the amount of precipitation. Model recharge was determined as a percentage of the average annual precipitation for each hydrogeologic unit.

Table 3.--Median depth to water table for different topographic settings

[General lithologies: C, carbonate rocks; M, metamorphic rocks; PS, Paleozoic sedimentary rocks; TS, Triassic sedimentary rocks.]

Hydrogeologic unit and general lithology		Median depth, in feet below land surface 1/				
		Hilltop	Upper slope	Middle slope	Lower slope	Valley bottom
1	C	-	-	34	18	10
2	C	-	45	30	15	10
3	C	-	45	35	15	10
4	C	-	55	32	23	15
5	C	-	45	30	15	10
6	C	-	50	30	20	-
7	C	-	-	35	15	-
8	C	-	40	28	15	8
9	C	-	-	34	18	-
10	C	-	-	35	15	-
11	C	-	-	35	15	-
12	M	85	65	38	25	15
13	PS	45	35	30	15	-
14	M	85	65	38	-	-
15		-	50	36	20	-
16	C	-	45	34	15	-
17	C	-	45	34	18	10
18	TS	85	60	35	25	-
19	TS	100	75	48	35	-
20		30	25	20	15	-
21	TS	40	30	21	12	-
22	TS	93	68	42	-	-

1/ Dash indicates no model grid blocks are present with the assigned topographic setting.

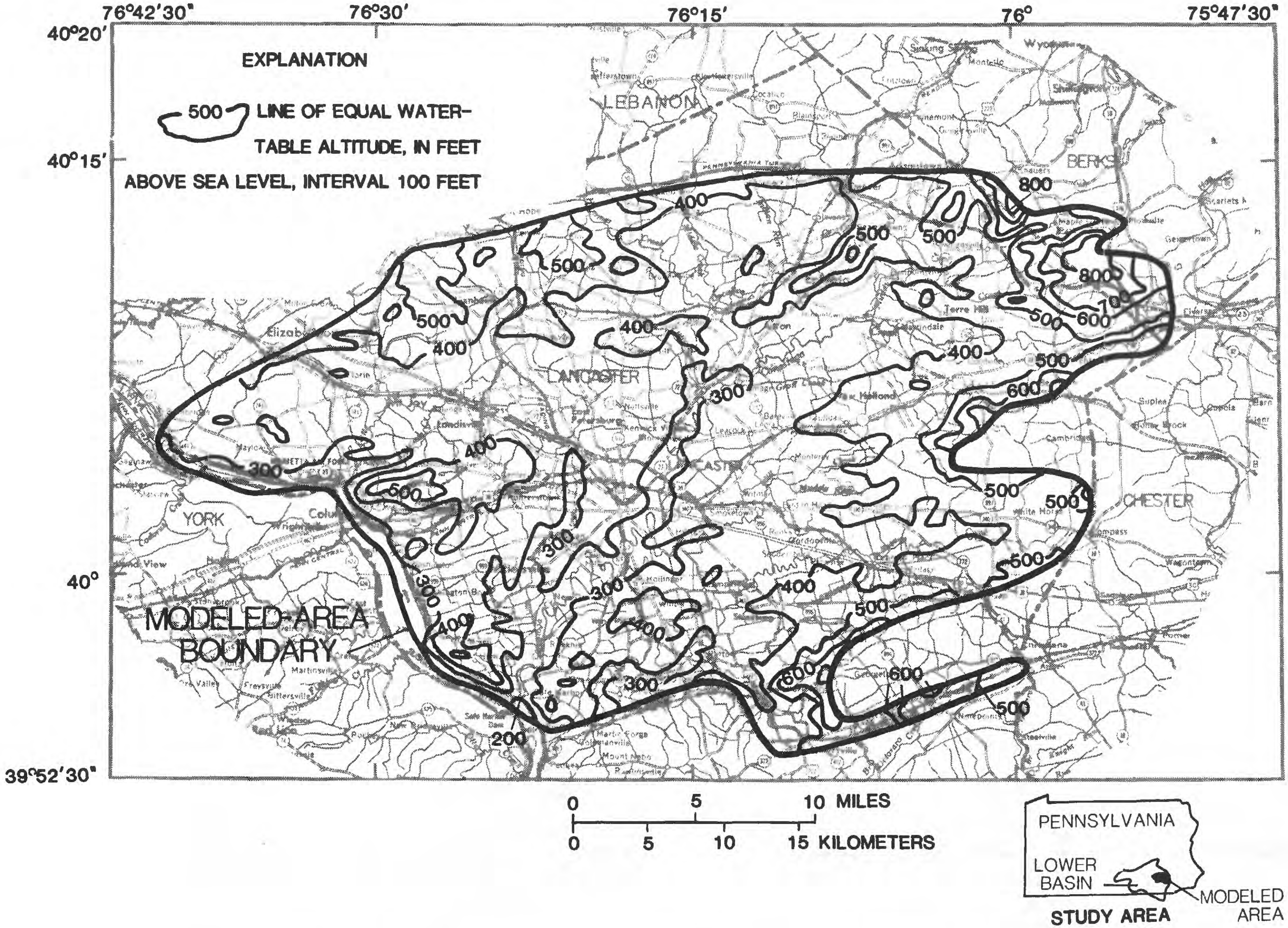


Figure 8.--Estimated water-table altitude in modeled area.

Model recharge was assumed to equal average annual base flow, because there is no net gain or loss of ground water from storage during an average year. Base flows during years with near-average (when possible) precipitation were estimated for six streams within and adjacent to the modeled area (table 4). A graphical separation technique was applied to U.S. Geological Survey streamflow hydrographs to obtain base flows (Linsley and others, 1949, p. 400). In this technique, the prior recession curve is extended to a point directly below a streamflow peak. From there, a straight line is drawn up to a point on the current recession curve N days after the peak, where N is a factor based on drainage area. By use of precipitation data from NOAA stations in or near each stream basin, the estimated base flow was converted to a percentage of annual precipitation (table 4). These percentages were assumed to be average annual percentages. The percentage for Pequea Creek was calculated for two years with very different precipitation totals in order to check the sensitivity of the percentage to total precipitation; the resulting percentages were nearly the same (table 4).

Each of the six stream basins contains more than one hydrogeologic unit. The percentage of precipitation that is base flow is different for each unit due to differences in lithology. Initial percentages were assigned to each unit in each stream basin based on percentages of similar lithologies in the lower-basin evaluation (Gerhart and Lazorchick, 1984). These percentages were then modified until their combined area-weighted averages for each basin approximated the overall basin percentage in table 4. The average percentage of annual precipitation that is base flow (table 5) is about 36 for carbonate units, 28 for Paleozoic sedimentary units, 25 for metamorphic units, and 20 for Triassic sedimentary units. These averages, as well as many other such averages in the report, are area-weighted averages of the values for each unit of a general lithology.

Each grid block was assigned the base-flow percentage (table 5) associated with the unit in which it is located. This percentage for each grid block was then multiplied by the average annual precipitation (fig. 3) for each grid block to determine the recharge rate used in the steady-state calibration. This recharge rate (in/yr) for each grid block was converted to a volumetric rate (ft^3/s) and added for those parts of the six stream basins in the modeled area; this resulted in an estimated average annual base flow for each of those areas (fig.9).

Ground water lost to consumptive withdrawals does not appear in streams as base flow. Therefore, model recharge equal to base flow is less than actual recharge from precipitation. The amount of actual recharge lost to consumptive withdrawals in the area was minor. Based on water-use data reported to the Pennsylvania Department of Environmental Resources from 1972 through 1979 by major users (Runkle, written commun., 1980), less than 11 Mgal/d of ground-water use occurs in the modeled area. Consumptive use probably is even less. This is about 3 percent of the estimated model recharge.

Similarly, the amount of actual recharge lost to ground-water evapotranspiration is not included in model recharge. It also was assumed to be relatively minor. McGreevy and Sloto (1980) used an annual recharge of about 17.7 inches for the crystalline rocks of Chester County. They estimated that

Table 4.--Data used to calculate percentage of precipitation that is base flow for gaged streams

Gaged stream 1/	Drainage area, in square miles	Year of record	Streamflow, in inches	Base flow, in inches	Precipitation, in inches	Percentage of precipitation that is base flow
Chickies Creek at Manheim	29	10/1978-9/1979	22.59	14.21	53.27	26.7
Conestoga River at Lancaster 2/	324	10/1966-9/1967	12.57	9.05	41.78	21.7
Bowery Run near Quarryville	5.98	10/1966-9/1967	15.14	10.75	38.90	27.6
Little Conestoga Creek at Conestoga Country Club	38.2	11/1963-10/1964	16.45	13.82	34.97	39.5
Little Conestoga Creek at East Petersburg	14	10/1963-9/1964	13.80	11.59	33.29	34.8
Pequea Creek at Martic Forge	148	10/1977-9/1978	27.16	19.28	51.90	37.1
		10/1979-9/1980	17.48	15.16	37.32	40.6

1/ Locations of stream basins shown on figure 9.

2/ Gage is located downstream from intake for Lancaster Municipal Water Authority; diversion in 1979 was 0.47 inches.

Table 5.--Percentage of average annual precipitation that is base flow for each hydrogeologic unit

[General lithologies: C, carbonate rocks; M, metamorphic rocks; PS, Paleozoic sedimentary rocks; TS, Triassic sedimentary rocks.]

Hydrogeologic unit and general lithology		Percentage
1	C	45
2	C	40
3	C	40
4	C	35
5	C	35
6	C	28
7	C	28
8	C	28
9	C	28
10	C	28
11	C	28
12	M	25
13	PS	28
14	M	25
15		32.5
16	C	31.5
17	C	36.5
18	TS	20
19	TS	20
20		5
21	TS	20
22	TS	20

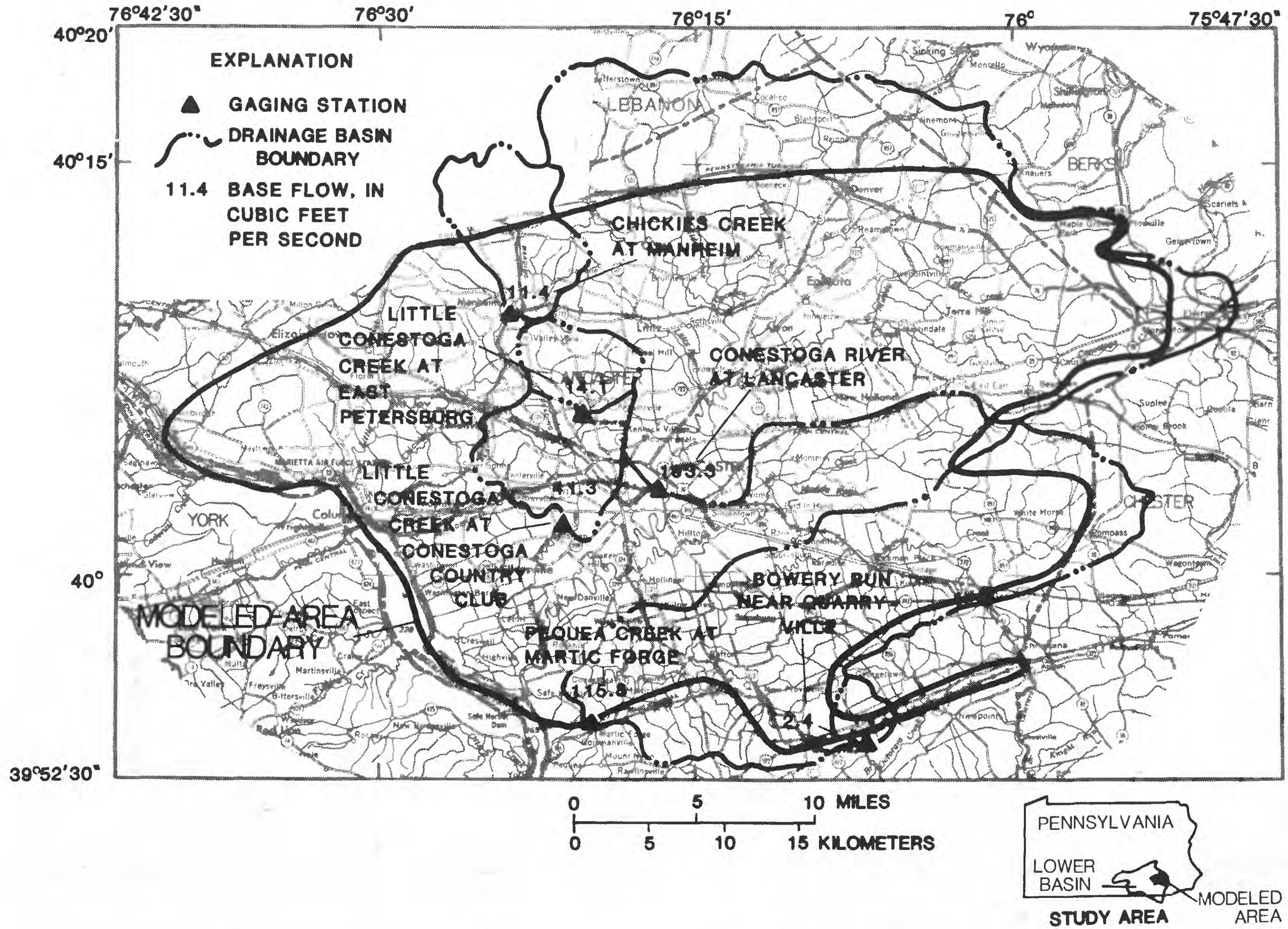


Figure 9.--Estimated average annual base flows for gaged streams in modeled area (base flows are for parts of streams in modeled area).

about 2.7 inches, or 15 percent, of that recharge was lost to evapotranspiration. Ground-water evapotranspiration in this investigation probably is a much smaller percentage of total recharge because water levels generally are deeper below land surface than in the crystalline rocks of Chester County. For this reason, and due to the lack of data on its distribution and magnitude, ground-water evapotranspiration was not included in model recharge. Omitting the amounts of ground water lost to consumptive withdrawals and evapotranspiration results in underestimation of the ground-water resources.

Hydraulic Conductivity

Initial Estimates

The median specific capacities reported in Meisler and Becher (1971), Wood (1981), and Poth (1977) were converted to average hydraulic conductivities for the 22 hydrogeologic units. A conversion factor based on the relation between specific capacities and adjusted hydraulic conductivities in the lower-basin model (Gerhart and Lazorchick, 1984) was obtained by use of the following equation:

$$F = \frac{11.36}{2.00} = 5.68 \qquad (1)$$

where F = conversion factor;

11.36 = calibration value of average hydraulic conductivity for the northern Conestoga Valley carbonate rocks east of the Susquehanna River from the lower-basin evaluation (Gerhart and Lazorchick, 1984), in feet per day;

2.00 = weighted average of the median specific capacities for those same carbonate rocks, in gallons per minute per foot of drawdown.

This factor was then multiplied by the median specific capacity for each unit to obtain initial estimates of average hydraulic conductivity (table 6). Hydraulic conductivities along model grid rows and columns initially were assumed to be equal. The Stonehenge Formation (unit 1) has the greatest initial estimates of average hydraulic conductivity (85.2 ft/d); diabase (unit 20) has the least (0.6 ft/d).

These average hydraulic conductivities were assumed to apply for grid blocks with middle-slope topographic setting. Specific-capacity data indicate that wells in higher topographic settings have lower specific capacities than wells in lower topographic settings. Therefore, the average hydraulic conductivity for grid blocks with upper-slope and hilltop settings was multiplied by a factor (less than 1.0) that was determined from the relation between specific capacity and topographic setting for the appropriate hydrogeologic unit; this resulted in calculated hydraulic conductivities less than the average. By a similar process, grid blocks with lower-slope and valley-bottom settings were assigned hydraulic conductivities greater than the average. Initial estimates of these multiplication factors are shown in table 7.

Adjustments

In order to obtain agreement between model-generated and estimated water-table altitudes during steady-state calibration, the initial estimates of average hydraulic conductivity and multiplication factors for topographic effect were adjusted for some hydrogeologic units. The calibration values of average hydraulic conductivity are shown in table 6. They are less than the initial estimates for 13 units, greater for 6 units, and the same for 3 units. All adjustments were within an order of magnitude, with the exception of that for the Wissahickon Formation (unit 14), which was decreased by a factor of 14. The calibration values of average hydraulic conductivity average about 8.8 ft/d for carbonate units, 2.0 ft/d for Paleozoic sedimentary units, 1.2 ft/d for Triassic sedimentary units, and 0.5 ft/d for metamorphic units.

In the dipping Triassic sedimentary units, secondary permeability is greater parallel to the strike of bedding than perpendicular to strike. During steady-state calibration, ratios of 5:1, 10:1, and 100:1 were used for hydraulic conductivity parallel to strike (rows) versus hydraulic conductivity perpendicular to strike (columns). The average hydraulic conductivity was maintained through use of the equations:

$$HCPARA = \frac{2\ AHC}{(1/R + 1)} \qquad (2)$$

$$HCPERP = \frac{2\ AHC}{R + 1} \qquad (3)$$

where
$HCPARA$ = hydraulic conductivity parallel to strike;
$HCPERP$ = hydraulic conductivity perpendicular to strike;
AHC = average hydraulic conductivity;
R = ratio of $HCPARA$ to $HCPERP$.

The simulation in which hydraulic conductivity parallel to strike was five times greater than hydraulic conductivity perpendicular to strike yielded the best agreement between model-generated and estimated water-table altitudes in Triassic sedimentary units. Consequently, anisotropy of 5:1 was used in units 18, 19, 21, and 22 (table 6). In all other units, hydraulic conductivities in the two model directions are equal.

The calibration values of the multiplication factors for topographic effect are shown in table 7. The initial multiplication factors were adjusted in six units (12, 18-22). In all six, the factors for hilltop and upper-slope topographic settings were reduced in order to yield hydraulic conductivities that are approximately five times lower than the initial estimates under hilltops and approximately three times lower under upper slopes.

Hydraulic conductivity used in the model is the product of the average hydraulic conductivity for each unit (table 6) and the multiplication factor for each topographic setting for each unit (table 7). The resulting hydraulic conductivities range from 1,048 ft/d under valley bottoms in the Stonehenge Formation (unit 1) to 0.01 ft/d under hilltops in diabase (unit 20).

Table 6.--Initial estimates of average hydraulic conductivity and average hydraulic conductivities used in calibrated model

[General lithologies: C, carbonate rocks; M, metamorphic rocks; PS, Paleozoic sedimentary rocks; TS, Triassic sedimentary rocks.]

Hydrogeologic unit and general lithology		Average hydraulic conductivity, in feet per day	
		Initial estimate	Calibration value
1	C	85.2	85.2
2	C	14.2	7.0
3	C	13.6	5.0
4	C	3.1	5.0
5	C	2.8	1.0
6	C	1.1	1.1
7	C	1.1	3.0
8	C	.9	1.5
9	C	.8	2.5
10	C	.8	2.5
11	C	3.4	1.0
12	M	1.1	.5
13	PS	1.1	2.0
14	M	7.0	.5
15		7.4	1.5
16	C	3.1	1.5
17	C	42.6	42.6
18	TS	2.6	1.2 (2.00, .40)1/
19	TS	2.6	2.0 (3.33, .67)1/
20		.6	.1
21	TS	4.7	1.2 (2.00, .40)1/
22	TS	2.6	1.2 (2.00, .40)1/

1/ First parenthesized value is hydraulic conductivity in east-west direction; second is hydraulic conductivity in north-south direction.

Table 7.--Initial estimates of multiplication factors used to modify average hydraulic conductivity for topographic effect and multiplication factors used in calibrated model

[General lithologies: C, carbonate rocks; M, metamorphic rocks; PS, Paleozoic sedimentary rocks; TS, Triassic sedimentary rocks.]

Hydrogeologic unit and general lithology		Multiplication factors									
		Initial estimates					Calibration values				
		Hilltop	Upper slope	Middle slope	Lower slope	Valley bottom	Hilltop	Upper Slope	Middle slope	Lower slope	Valley bottom
1	C	0.3	0.7	1.0	6.7	12.3	0.3	0.7	1.0	6.7	12.3
2	C	.3	.7	1.0	1.1	1.2	.3	.7	1.0	1.1	1.2
3	C	.4	.7	1.0	2.0	3.0	.4	.7	1.0	2.0	3.0
4	C	.1	.6	1.0	2.2	3.3	.1	.6	1.0	2.2	3.3
5	C	.4	.7	1.0	2.0	3.0	.4	.7	1.0	2.0	3.0
6	C	.5	.8	1.0	1.9	2.7	.5	.8	1.0	1.9	2.7
7	C	.5	.8	1.0	1.9	2.7	.5	.8	1.0	1.9	2.7
8	C	.1	.6	1.0	2.0	3.0	.1	.6	1.0	2.0	3.0
9	C	.5	.8	1.0	1.9	2.7	.5	.8	1.0	1.9	2.7
10	C	.4	.7	1.0	2.0	3.0	.4	.7	1.0	2.0	3.0
11	C	.4	.7	1.0	2.0	3.0	.4	.7	1.0	2.0	3.0
12	M	.6	.8	1.0	1.7	2.3	.1	.3	1.0	1.7	2.3
13	PS	.6	.8	1.0	1.5	2.0	.6	.8	1.0	1.5	2.0
14	M	.2	.5	1.0	1.3	1.5	.2	.5	1.0	1.3	1.5
15		.5	.8	1.0	1.9	2.7	.5	.8	1.0	1.9	2.7
16	C	.4	.7	1.0	2.0	3.0	.4	.7	1.0	2.0	3.0
17	C	.4	.7	1.0	4.4	7.7	.4	.7	1.0	4.4	7.7
18	TS	.6	.8	1.0	1.2	1.5	.1	.3	1.0	1.2	1.5
19	TS	.5	.8	1.0	1.2	1.5	.1	.3	1.0	1.2	1.5
20		.8	.9	1.0	1.2	1.3	.1	.3	1.0	1.2	1.3
21	TS	.5	.8	1.0	1.2	1.5	.1	.3	1.0	1.2	1.5
22	TS	.5	.8	1.0	1.2	1.5	.1	.3	1.0	1.2	1.5

Stream Leakage Coefficients

Initial Estimates

Much of the recharge to and discharge from the ground-water flow system occurs locally. Some of the water recharging a grid block may discharge to streams or lakes within that same block. Because 55 percent of the grid blocks contain either a stream or lake, a mechanism for handling this local phenomenon was incorporated in the model. (For convenience, because streams greatly outnumber lakes, the rest of the report will refer to streams as including streams and lakes.)

A head-dependent stream leakage option was used to account for recharge and discharge within the same grid block. (See Gerhart and Lazorchick, 1984 for a more detailed discussion). This option (Tracy, written commun., 1979) permits use of a constant stream altitude for a grid block without the drawback of having to assign a constant water-table altitude to the block. Then, as water-table altitude varies during simulation, the flow between the stream and the aquifer varies according to the difference between stream and water-table altitudes for the block.

For a grid block with a gaining stream, ground water may discharge from the aquifer to the stream either through the streambed or adjacent to the stream as seeps and springs. Streambeds generally are bedrock overlain by a thin, discontinuous layer of alluvium of various sizes. Discharge through adjacent seeps and springs probably is much greater than discharge through streambeds.

On the other hand, for a grid block with a losing stream, the aquifer is recharged only from leakage through the streambed. Therefore, the stream leakage coefficient is less when the stream is losing. Although it was assumed that there are no losing streams in the area on an average annual basis, gaining streams may become losing streams when a stress is imposed. In order for the model to accurately simulate such a condition, two stream leakage coefficients were determined for each grid block with a stream--one each for gaining- and losing-stream conditions.

In order to obtain an initial estimate of gaining-stream leakage coefficient for each unit (table 8), the following equation was used:

$$C = B \Big/ \sum_{1}^{n} p(h_{WT}-h_{S}) \qquad (4)$$

where

C = gaining-stream leakage coefficient for the unit, in feet per second;

B = total estimated base flow for the unit, in cubic feet per second;

n = number of grid blocks in the unit that contain streams;

p = perimeter of streams for the grid block, in feet;

h_{WT} = estimated water-table altitude for the grid block, in feet above sea level;

h_{S} = stream altitude for the grid block, in feet above sea level.

In this way, gaining-stream leakage coefficient was made uniform within a unit, and is the coefficient necessary to discharge average annual recharge from that unit under estimated water-table and stream altitudes.

Losing-stream leakage coefficients were needed for situations in which the water-table altitude for a grid block might drop below the stream altitude. Because there were no perennially losing streams in the area, the ratios of gaining to losing coefficients determined in the lower-basin evaluation (Gerhart and Lazorchick, 1984) were used to assign the losing-stream leakage coefficients. A ratio of 2:1 was used for those units containing carbonate rocks; 10:1 was used for Paleozoic sedimentary, Triassic, and metamorphic units; and 3:1 was used for unit 15, which is a combination of carbonate and metamorphic rocks.

In a losing stream, the rate of flow from the stream to the aquifer increases as water-table altitude decreases until a certain altitude is reached. This altitude, the stream-discharge cutoff altitude, is the point at which a stream becomes hydraulically separated from an aquifer. When the water-table altitude drops below this cutoff altitude, an unsaturated portion of aquifer separates the stream and the water table below the stream. From then on, the rate of flow from the stream to the aquifer will not increase, but will remain at the rate that was in effect when the cutoff altitude was reached.

The cutoff altitude for each grid block was based on the average depth of streams for the block. Average depths of 10, 5, and 2 ft were estimated for the Susquehanna River, major tributaries, and small streams, respectively. An average depth of 30 ft was estimated for reservoirs and an average depth of 5 ft was estimated for lakes. A weighted average of the above depths was calculated for blocks containing more than one of these water bodies.

Table 8.--Initial estimates of gaining-stream leakage coefficient, and gaining-stream leakage coefficients used in calibrated model

[General lithologies: C, carbonate rocks; M, metamorphic rocks; PS, Paleozoic sedimentary rocks; TS, Triassic sedimentary rocks.]

Hydrogeologic unit and general lithology		Gaining-stream leakage coefficient, in feet per day	
		Initial estimate	Calibration value
1	C	3.241	3.241
2	C	2.026	1.520
3	C	.525	.302
4	C	4.572	4.572
5	C	1.459	1.459
6	C	.883	.883
7	C	.911	4.558
8	C	1.262	1.262
9	C	3.361	16.805
10	C	2.082	2.082
11	C	1.286	2.571
12	M	.297	.198
13	PS	.214	.107
14	M	.102	.021
15		.285	.071
16	C	1.677	2.095
17	C	4.049	3.240
18	TS	.619	.619
19	TS	1.148	.800
20		.032	.021
21	TS	.400	.200
22	TS	.622	.156

The average depth of surface water for each block was then subtracted from the stream altitude to obtain the cutoff altitude for each block.

Flow between an aquifer and a stream for a grid block also is dependent on the density of streams for the block. For any hydrogeologic unit, a block with several miles of streams will have more flow between aquifer and stream than a block with only 1 mile of streams. To incorporate this in the model, the gaining- and losing-stream leakage coefficients for each block were weighted according to stream density for each block. The total perimeter of streams was used as the weighting factor. The stream leakage coefficients for each unit were multiplied by the total perimeter of streams for each block to obtain weighted stream leakage coefficients for each block.

Adjustments

The initial estimates of stream leakage coefficients for 15 hydrogeologic units were adjusted during steady-state calibration in order to obtain agreement between model-generated and estimated water-table altitudes. The final calibration values are shown in table 8. The calibration values are less than the initial estimates for 11 units and greater for 4 units. The maximum adjustment was an increase by a factor of 5.0 for the Richland Formation (unit 9) and the Millbach Formation (unit 7). The initial ratios of gaining- to losing-stream leakage coefficient were maintained in the final calibration values.

The calibration values of gaining-stream leakage coefficients (table 8) range from 0.021 ft/d for the Wissahickon Formation (unit 14) and diabase (unit 20) to 16.805 ft/d for the Richland Formation (unit 9). The average calibration values of gaining-stream leakage coefficient are 1.83 ft/d for carbonate units, 0.49 ft/d for Triassic sedimentary units, 0.16 ft/d for metamorphic units, and 0.11 ft/d for Paleozoic sedimentary units.

Boundary Conditions

The steady-state boundary conditions are shown in figure 10. A no-flow boundary condition initially was used along the northeastern edge of the area because that portion of the boundary corresponds to the basin boundary of the Susquehanna River, and the ground-water divide there was assumed to correspond to the surface drainage divide. The model was not very sensitive to boundary conditions there, so the initial no-flow boundary conditions were not changed. A constant-head boundary condition was used for the Susquehanna River along the southwestern edge of the area. It was assumed that heads in the aquifer for these blocks are equal to the river altitude.

The northern and southern edges of the area were designated constant-flux boundaries. Ground-water flow across these boundaries was determined by Darcy's law--that is, ground-water flow between two grid blocks on either side of a constant-flux boundary is a function of their hydraulic conductivities, their estimated water-table altitudes, and grid spacing. As a result, some units may have net boundary inflow and some units net outflow. The water-table altitudes for grid blocks not immediately adjacent to these boundaries were not significantly affected by the choice of boundary conditions.

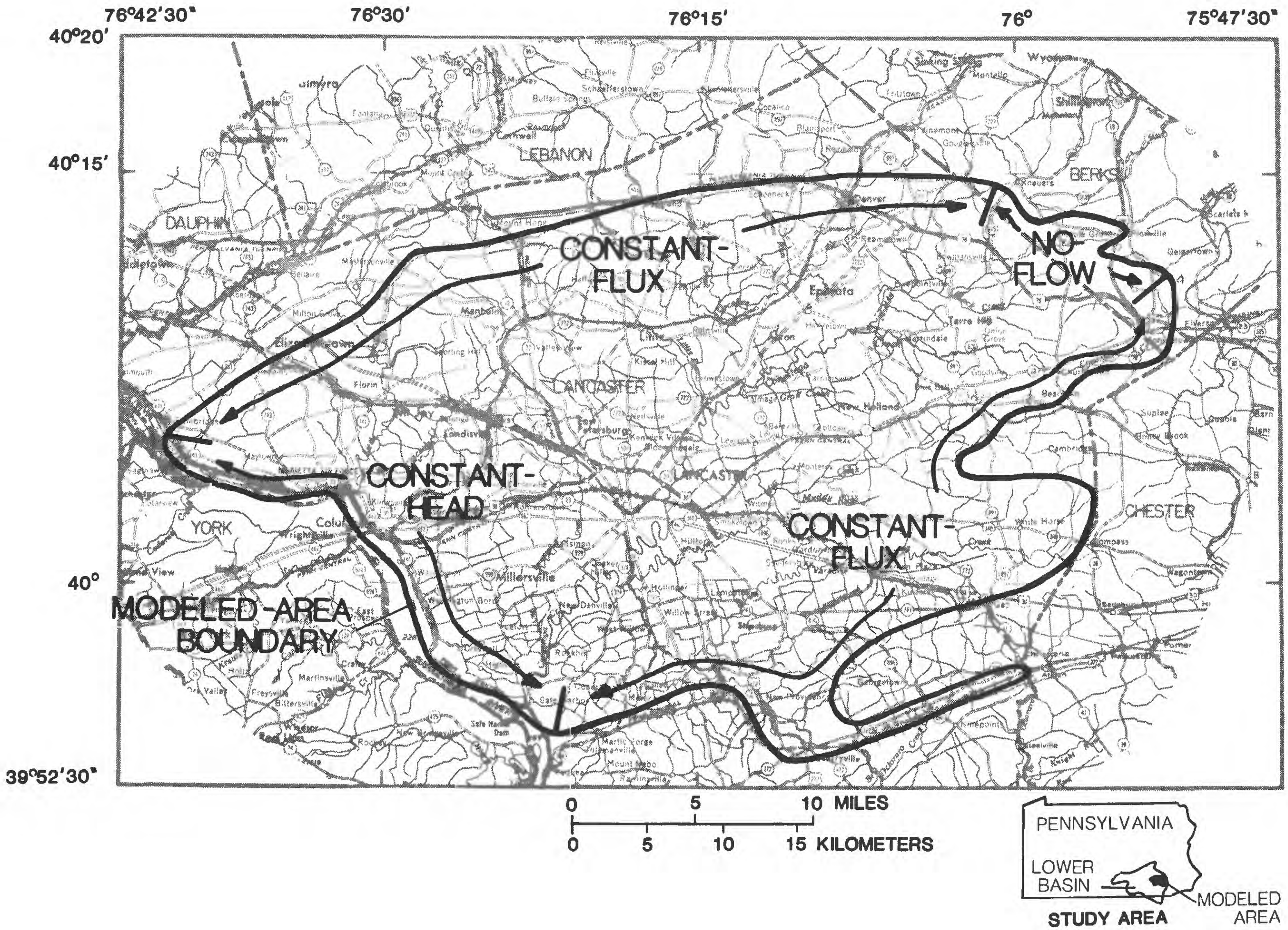


Figure 10.--Delineation of steady-state boundary conditions.

Results

Water-Table Altitudes

Non-parametric statistics were used to judge the adequacy of the steady-state calibration. The difference between the estimated and model-generated water-table altitude was calculated for each grid block. The median difference was then determined for each unit. In addition, four other percentiles--10, 25, 75, and 90--were used to evaluate the spread of differences around the median. The calibration goals were to obtain a median difference of zero for each unit and to minimize the 10 and 90 percentiles. By meeting these goals, it was decided that the accuracy of the model would be in proper agreement with the accuracy of the hydrologic data and with the averaging methods used to incorporate those data in the model.

A problem with using statistics to judge calibration is that the areal distribution of differences is not considered. Therefore, in addition to the statistical analysis, the distributional biases were examined. For example, a unit may have positive differences in its eastern half and an equal number of negative differences in its western half, and show a median difference of zero and low 10 and 90 percentiles. But, obviously, the hydrologic characteristics used in the model to describe that unit are inappropriate. No such problems occurred for any of the units in this investigation; the map that shows model-generated water-table altitudes (fig.11) generally is the same, in all areas, as the map that shows estimated water-table altitudes (fig. 8).

The statistics describing the calibration are shown in table 9. As an example, the results for the Stonehenge Formation (unit 1) show good agreement between model-generated and estimated water-table altitudes. The median difference is 1.1 ft; more than 50 percent of the differences are less than 7 ft and more than 80 percent are less than 15 ft. This range of differences is considered within the range of uncertainty for estimated water-table altitudes for grid blocks approximately one-sixth of a square mile in area.

The following table shows selected statistics for all units combined, as well as for carbonate and noncarbonate units:

	Number of grid blocks	Percentiles of difference between estimated and model-generated water-table altitudes, in feet		
		10	median	90
All units	3,712	24.6	1.9	-28.0
Carbonate units	2,580	21.1	1.9	-21.9
Noncarbonate units	1,023	34.7	1.1	-40.0

For the entire modeled area, more than 80 percent of the differences are less than 30 ft. For carbonate units, more than 80 percent are less than 22 ft,

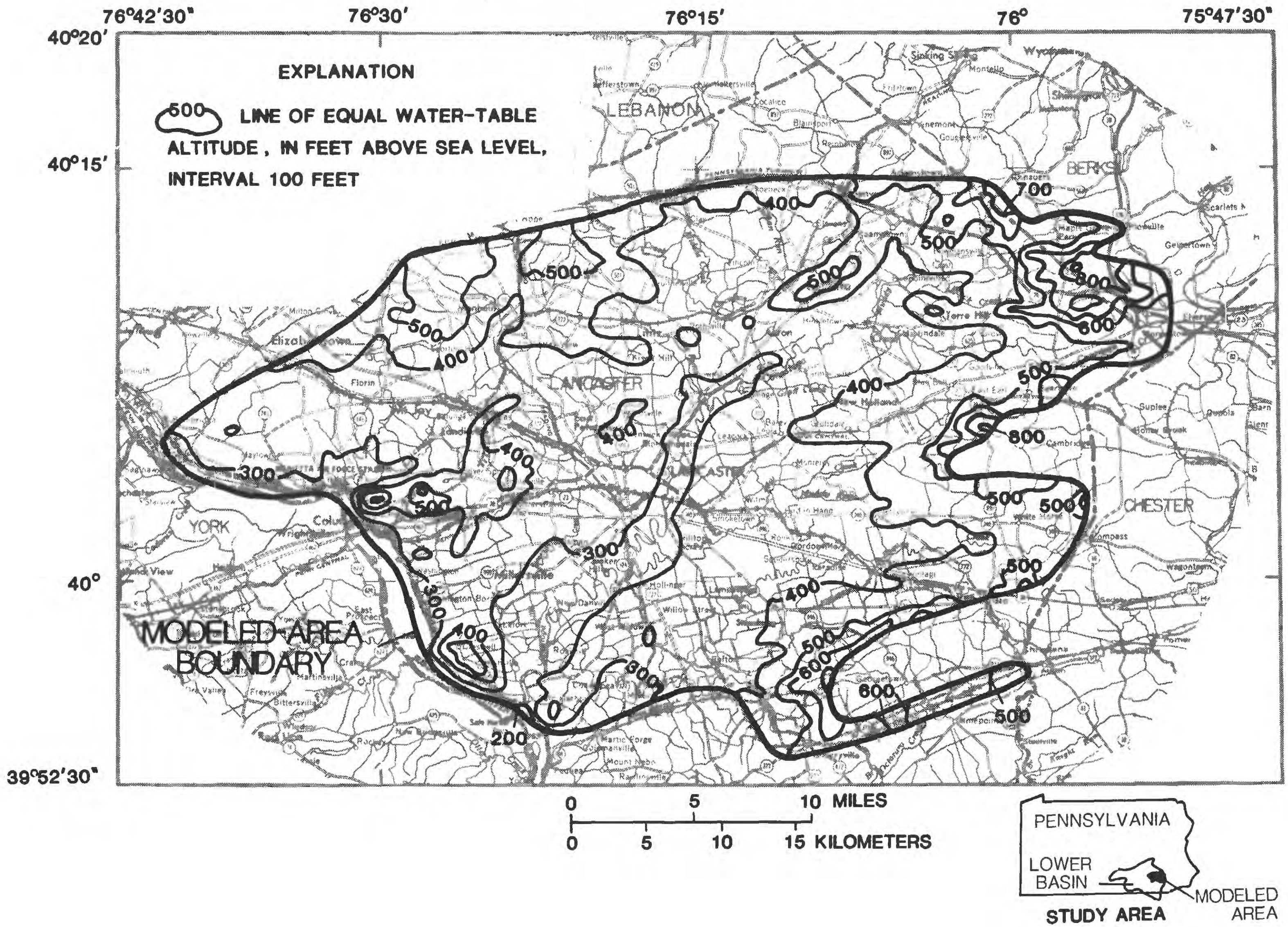


Figure 11.--Water-table altitude generated in calibrated steady-state model.

Table 9.--Statistical comparison, by hydrogeologic unit, of estimated water-table altitudes and water-table altitudes generated in calibrated steady-state model

[General lithologies: C, carbonate rocks; M, metamorphic rocks; PS, Paleozoic sedimentary rocks; TS, Triassic sedimentary rocks.]

Hydrogeologic unit and general lithology		Number of grid blocks in unit	Percentiles of differences between estimated and model-generated water table altitude, in feet[1/]				
			10	25	Median	75	90
1	C	118	14.8	6.9	1.1	-6.9	-15.0
2	C	410	15.8	7.7	3.3	-4.2	-19.8
3	C	737	25.6	17.9	3.9	-15.3	-34.9
4	C	340	17.7	7.0	1.3	-4.2	-14.4
5	C	122	17.6	5.1	2.2	-5.5	-19.3
6	C	282	14.3	6.3	.8	-7.8	-20.3
7	C	89	15.5	9.1	1.0	-8.8	-18.4
8	C	257	16.1	7.6	1.1	-5.1	-14.8
9	C	14	36.0	17.0	.7	-1.3	- 8.8
10	C	35	21.5	6.9	.3	-9.7	-15.3
11	C	23	28.3	5.9	-1.1	-11.0	-18.8
12	M	215	42.9	13.0	-1.4	-21.7	-43.7
13	PS	359	30.7	16.7	1.9	-17.3	-35.7
14	M	57	56.7	26.4	0	-15.4	-50.1
15		109	30.1	22.1	3.1	-15.1	-47.3
16	C	80	24.7	4.5	2.1	-6.2	-16.0
17	C	73	17.1	7.7	1.4	-11.2	-26.8
18	TS	195	37.2	10.5	3.6	-13.4	-33.0
19	TS	33	29.9	7.4	1.5	-14.2	-63.7
20		49	43.3	19.1	4.2	-22.5	-51.9
21	TS	64	21.2	8.8	-1.2	-24.4	-54.9
22	TS	51	35.4	24.3	7.6	-21.8	-59.5

[1/] Negative differences indicate model-generated water-table altitude is less than estimated water-table altitude.

whereas for noncarbonate units, more than 80 percent are less than 40 ft. The main reason for the poorer agreement for noncarbonate units is that the local relief is greater there, making it difficult to estimate accurately average water-table altitudes. In addition, hydrologic characteristics differ more over shorter distances in Triassic sedimentary units than in other units, making it less likely that the characteristics can be represented by average values.

Base Flows

As discussed in the section on recharge, base flow was estimated for six streams in the modeled area (fig. 9). As a further check on the adequacy of the steady-state calibration, base flows generated in the model for these six streams were compared to estimated base flows (table 10). Model-generated base flows are within 6 percent of estimated base flows, except for Bowery Run near Quarryville, where the model-generated base flow is within 13 percent of the estimated base flow. The differences probably are due to the slight shifting of ground-water divides where model-generated water-table altitudes for grid blocks near the divides deviate from the estimated altitudes. Such differences were considered within the range of error associated with hydrograph-separation techniques.

Ground-Water Budgets

The flow rates into and out of each grid block were added for the entire area to obtain an overall average annual ground-water budget. Annually, an average of about 388 Mgal/d is discharged to streams. About 96 percent of that discharge is model recharge (from precipitation); about 3 percent is infiltration from streams; and about 1 percent is flow across model boundaries.

The flow rates for each grid block also were added by hydrogeologic unit to obtain an average annual ground-water budget for each unit. These total flow rates for each unit were then normalized with respect to area by dividing by the area of the unit (table 11). Model recharge is greatest [0.87 (Mgal/d)/mi2] for the Stonehenge Formation (unit 1) and least [0.10 (Mgal/d)/mi2] for diabase (unit 20). The Stonehenge Formation (unit 1) also gains the most ground water from infiltration from streams [0.09 (Mgal/d)/mi2]. The unit containing the Stonehenge Formation and parts of other carbonate units (unit 17) gains the most ground water from adjacent units [2.88 (Mgal/d)/mi2] and loses the most to adjacent units [2.23 (Mgal/d)/mi2]. Considering the total sources for each unit, this same unit (17) has the greatest overall recharge, 3.62 (Mgal/d)/mi2. The least overall recharge is 0.11 (Mgal/d)/mi2 for diabase (unit 20). Because total sinks balance total sources, the units with the greatest and the least total sinks also are units 17 and 20, respectively.

Carbonate, Paleozoic sedimentary, metamorphic, and Triassic sedimentary units have average rates of model recharge of 0.66, 0.55, 0.40, and 0.39 (Mgal/d)/mi2, respectively. Infiltration from streams occurs only in carbonate units and averages 0.04 (Mgal/d)/mi2. Carbonate units have the greatest average gain of ground water from adjacent units, 0.45 (Mgal/d)/mi2,

Table 10.--Comparison, by gaged stream, of estimated base flows and base flows generated in calibrated steady-state model

Stream	Base flow, in cubic feet per second 1/ Estimated	Model-generated
Chickies Creek at Manheim	11.4	10.8
Conestoga River at Lancaster	193.3	192.1
Bowery Run near Quarryville	2.4	2.7
Little Conestoga Creek at Conestoga Country Club	41.3	38.9
Little Conestoga Creek at East Petersburg	14.1	13.6
Pequea Creek at Martic Forge	115.8	117.0

1/ Base flow is only for those parts of stream basins in modeled area.

Table 11.--Average annual ground-water budget for each hydrogeologic unit

[General lithologies: C, carbonate rocks; M, metamorphic rocks; PS, Paleozoic sedimentary rocks; TS, Triassic sedimentary rocks.]

Hydrogeologic unit and general lithology		Sources: Model recharge	Sources: Boundary flow	Sources: Infiltration from streams	Sources: Flow from adjacent units	Sources: Total	Sinks: Discharge to streams	Sinks: Boundary flow	Sinks: Flow to adjacent units	Sinks: Total
1	C	0.87	0.0	0.09	1.97	2.93	1.35	0.0	1.58	2.93
2	C	.72	.03	.02	0.37	1.14	0.97	0	0.17	1.14
3	C	.73	.01	0	.16	0.90	.83	0	.07	0.90
4	C	.66	.01	.07	.53	1.27	.80	0	.47	1.27
5	C	.63	.03	0	.43	1.09	.74	0	.35	1.09
6	C	.53	0	0	.23	.76	.46	0	.30	.76
7	C	.51	.01	.01	.44	.97	.66	0	.31	.97
8	C	.54	0	.01	.13	.68	.36	0	.32	.68
9	C	.53	0	0	.66	1.19	.77	0	.42	1.19
10	C	.54	0	.07	.50	1.11	.47	0	.64	1.11
11	C	.54	0	0	.28	.82	.34	0	.48	.82
12	M	.42	.04	0	.04	.50	.19	0	.31	.50
13	PS	.55	0	0	.01	.56	.32	.02	.22	.56
14	M	.33	0	0	.01	.34	.19	0	.15	.34
15		.59	.01	0	.26	.86	.29	.01	.56	.86
16	C	.59	0	.01	.44	1.04	.55	0	.49	1.04
17	C	.69	0	.05	2.88	3.62	1.39	0	2.23	3.62
18	TS	.39	.01	0	.10	.50	.41	0	.09	.50
19	TS	.39	0	0	.14	.53	.39	0	.14	.53
20		.10	0	0	.01	.11	.06	0	.05	.11
21	TS	.40	0	0	.12	.52	.20	0	.32	.52
22	TS	.38	0	0	.11	.49	.13	0	.36	.49

Flow rates, in million gallons per day per square mile.

as well as the greatest average loss to adjacent units, 0.37 (Mgal/d)/mi^2. The average overall recharge rates are 1.14, 0.56, 0.51, and 0.47(Mgal/d)/mi^2 for carbonate, Paleozoic sedimentary, Triassic sedimentary, and metamorphic units, respectively.

Sensitivity Analysis

Sensitivity analysis involves changing the value of a single input variable in a model and making another simulation. Any changes in results (model-generated water-table altitudes) are then due only to the change in that input variable. If the changes in results are great when a change is made to an input variable, the model is said to be sensitive to that variable. Conversely, slight changes in the results indicate model insensitivity to that variable.

Sensitivity analyses were performed on several key input variables prior to and during steady-state calibration. The results were used to guide adjustments of input variables during calibration. The sensitivity of the model to the following variables was analyzed: Model recharge, hydraulic conductivity, gaining- and losing-stream leakage coefficients, anisotropy, and boundary flow. The changes in model recharge, hydraulic conductivity, and stream leakage coefficients had the greatest overall effect on the results. As a result of the precalibration sensitivity analysis, it was decided that the steady-state calibration should involve the adjustment of hydraulic conductivity and stream leakage coefficients. Model recharge was considered the best defined of the three variables and was not adjusted.

After the steady-state calibration was completed, formalized sensitivity analyses for these three input variables were done with the steady-state calibration simulation as a base. The value of each input variable in the steady-state calibration was increased by 50 percent and three new simulations were made, one for each change in input variable. Model recharge generally had the greatest influence on model results (about 10 to 40 feet); hydraulic conductivity generally had the next greatest effect (about 5 to 20 feet); stream leakage coefficients generally had the least effect (less than 10 feet). The degree of sensitivity is related to lithology. Metamorphic units generally were the most sensitive and carbonate units were the least sensitive.

The sensitivity of Triassic units (18-22) to anisotropy also was analyzed with the steady-state calibration as a base. Anisotropy was increased from 5:1 to 25:1, while keeping the effective hydraulic conductivity of each unit the same as in the steady-state calibration. These units generally were not as sensitive to the increase in anisotropy as they were to the changes in model recharge, hydraulic conductivity, and stream leakage coefficients. However, for the Hammer Creek Conglomerate (unit 19), 25:1 anisotropy had as much effect on the model results as a 50-percent increase in model recharge.

The sensitivity of the model to boundary flow was analyzed by eliminating all boundary flow. The effects were insignificant for all units except the Cocalico Formation (unit 13), where they were nearly as great as the effects of a 50-percent increase in hydraulic conductivity. However, grid blocks adjacent to the boundary were the only ones to show significant effects.

CALIBRATION OF MODEL UNDER TRANSIENT CONDITIONS

General Procedure

The water table fluctuates in response to seasonal differences in recharge. The range of fluctuation depends partly on the specific yield of the aquifer. If a change in water-table altitude is observed and the differences in recharge can be estimated, the model can be used to determine the specific yield. In this investigation, the model was used to determine the specific yields of 11 formation groupings, each consisting of one to six hydrogeologic units.

Hydraulic conductivities, stream leakage coefficients, and boundary flows determined during the average annual steady-state calibration were used in the transient calibration. Recharge amounts for November 1, 1980 to April 22, 1981 were estimated and entered into the model along with initial estimates of specific yield. Model-generated changes in water-table altitude for each grouping were compared to those observed between November 1, 1980 and April 22, 1981. The initial estimates of specific yield were adjusted until model-generated and observed water-table changes were in statistical agreement; no other input variables were adjusted.

A network of 320 wells was established for the lower-basin evaluation (Gerhart and Lazorchick, 1984). A total of 68 of those wells are in the area of this investigation (plate 2). The water level in each well was measured in late October 1980 and mid-April 1981 (supplement I). The measurements were made with steel tape under static water-level conditions. Because most of the wells were less than 300 ft deep, the water levels were considered to be representative of the modeled upper portions of the aquifers.

All transient calibration simulations were for a period of slightly less than 9 months--August 1, 1980 through April 22, 1981. About 3 months were included prior to the October 1980 measurement of water levels (fig. 12), so that transient effects from recharge events before the measurement would be taken into account. Three months was considered to be sufficient lead time to account for most such effects.

Each simulation was accomplished by dividing the period of August 1, 1980 to April 22, 1981 into 10 recharge periods (fig. 12). Seven periods were a month in duration--August, September, November, December, January, February, and March. October was split into two periods--October 1-24 and October 25-31, the week of the October 1980 measurement. The last period was April 1-22, ending the week of the April 1981 measurement. Each period consisted of three time steps of increasing length.

The graph in figure 12 illustrates the transient-calibration procedure for one grid block (8-55) in hydrogeologic unit 4. The estimated model recharge rates indicate that, for this grid block, recharge generally decreased from October 1980 through January 1981, and then increased in

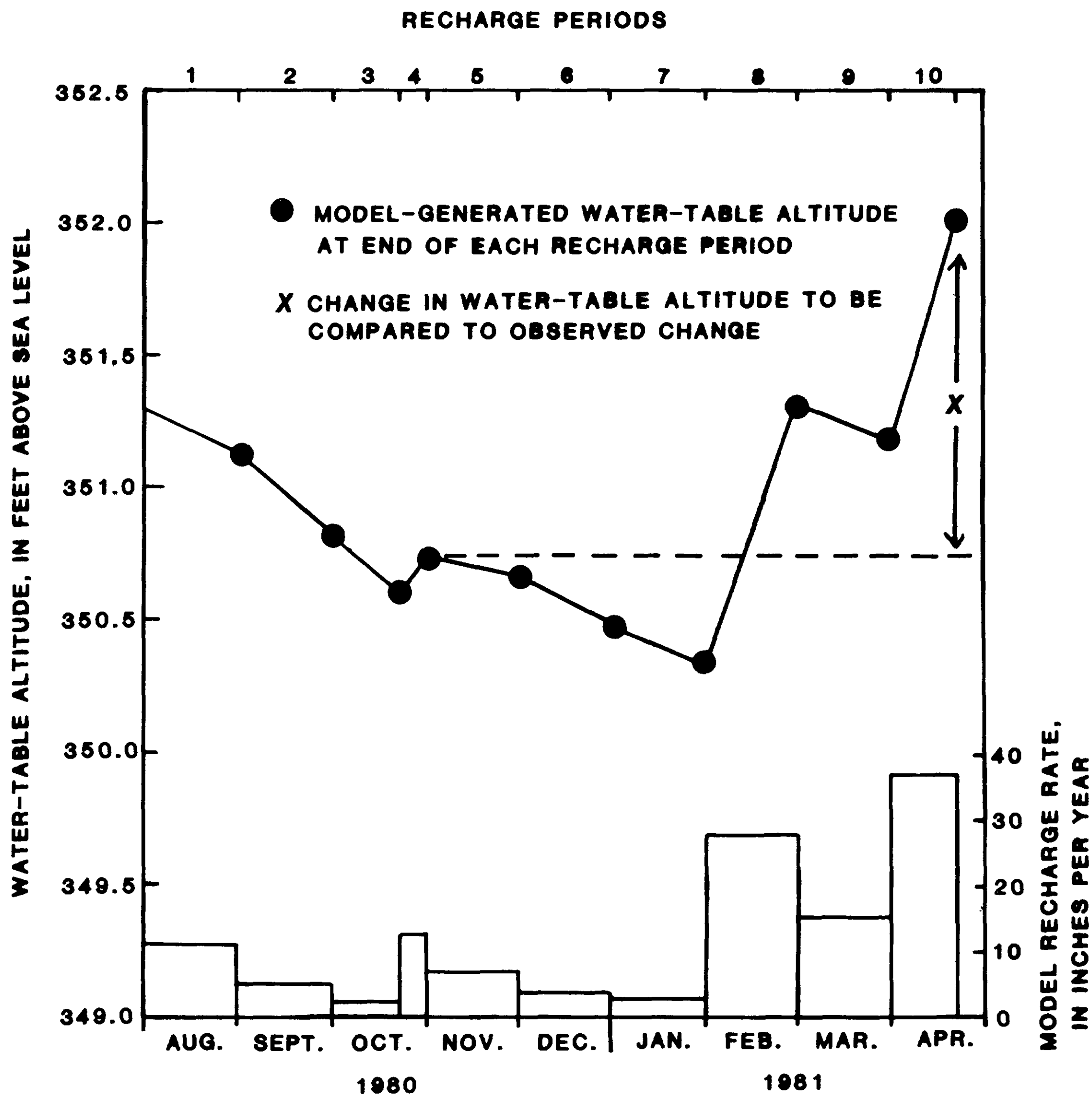


Figure 12.--Example of transient-calibration procedure for grid block 8-55.

February, March, and April of 1981. As shown, the use of these recharge rates resulted in model-generated water-table altitudes that follow the same trend. Model-generated changes in water-table altitude that were used to compare to observed changes between the October 1980 and April 1981 measurements were obtained by subtracting the water-table altitudes at the end of recharge period 4 from the altitudes at the end of recharge period 10. In this way, the model was calibrated against changes in water-table altitude, rather than absolute altitude, so that any errors in model-generated October 1980 altitudes would not affect the results. In grid block 8-55, the model-generated change (*X*) was an increase of about 1.3 ft.

Ground-Water Conditions

The starting point for each transient-calibration simulation--August 1, 1980--was about midway between the end of April and the end of October, usually the approximate times of annual highest and lowest water-table altitude, respectively. Therefore, water-table altitudes on August 1 probably were fairly close to average annual conditions. Consequently, the water-table altitudes generated in the average annual steady-state calibration were used as starting conditions for each transient-calibration simulation. Any errors introduced by these starting conditions were minimized by using the 3-month lead period.

Surface-Water Conditions

Steady-state surface-water conditions were used in the transient calibration because comprehensive data on changing surface-water conditions were lacking. Stream altitudes vary in response to changes in precipitation, but the large number of streams in the area precluded any synoptic measurement of their altitudes during the calibration period.

The altitudes of most streams probably did not change by more than a few feet between the October 1980 and April 1981 measurements. The calibration problems that arise from such an error in stream altitude may be significant only for those hydrogeologic units with low local relief. For those units, water-table and stream altitudes are about the same. Therefore, a slight change in stream altitude could reverse the direction of flow between the aquifer and the stream. Of the two stream basins for which stream-altitude data are available for the calibration period, the Conestoga River basin has the lowest local relief. The daily mean stage of the Conestoga River at the gage in Lancaster ranged from 2.76 to 4.60 ft above datum during the calibration period. It was assumed that such a small change in stream altitude would not significantly affect the calibration results.

Recharge

As in the steady-state calibration, model recharge for the 10 recharge periods in the transient calibration was determined as a percentage of precipitation. The percentages were estimated from U.S. Geological Survey streamflow hydrographs and NOAA precipitation data.

Recharge to the ground-water system was estimated for major storms during the 9-month transient-calibration period. A method developed by Rorabaugh (1964) and Daniel (1976) was used. Every stream has a characteristic slope of recession ($\Delta\tau$) which describes the dissipation of a flood impulse. This slope is influenced by the geometry and hydrologic characteristics of the basin and is the same for all floods. Once this slope is determined for a stream, the ground-water recharge from major storms can be estimated from the equation shown in figure 13. The calculation relies on the assumption that at a certain time, t_c, after a flood peak occurs, 50 percent of the ground-water recharge from the storm has entered the stream as base flow. Twice that amount, then, is the total ground-water recharge from the storm.

Because the method is based on streamflow, all the factors that affect recharge are taken into account. The effects of lithology, amount and intensity of precipitation, soil moisture, temperature, and other factors are included in the streamflow hydrographs. On the other hand, the method is based on several simplifying assumptions that were not strictly met in the stream basins in the area. For example, hydrologic characteristics and the distance from stream to basin divide should be uniform throughout the basin, and the water-table rise due to a storm should be uniform and instantaneous. Because these assumptions do not strictly apply in the basins in the area, recharge amounts calculated with this method are only estimates. But because these assumptions are the same for every storm, the calculated recharges are in the proper relation to each other. For example, calculated recharges of 0.5 and 1.5 inches for storms in November and March, respectively, may not be accurate, but the 1:3 ratio probably is accurate. Therefore, the recharge estimates obtained with this method were used only to define the relative proportions of recharge for each of the 10 recharge periods. These relative proportions then were used to distribute the estimated total recharge over the calibration period.

Recharge estimates were obtained in this manner for two gaged stream basins in the area. Eight storms in the Conestoga River basin and nine storms in the Pequea Creek basin were analyzed. The percentage of precipitation that recharged the ground-water system was obtained for each major storm for each basin by dividing estimated recharge by precipitation (fig. 13). Each basin was then represented by eight or nine percentages over the calibration period. The percentages were plotted against time and a curve was fitted to the data for each basin (fig. 14). The curves for both basins follow the same general trend--low percentages from August through November, increasing percentages from December through February, and decreasing percentages from March through April. For each basin, the average percentages of precipitation that are recharge were determined from the intersection of the curve with the midpoint of each recharge period.

The 22 units were organized into 11 formation groupings (table 12) on the basis of equal percentages of average annual precipitation that are base flow (table 5). Maintaining the overall basin percentages in figure 14 for each recharge period, percentages for the individual formation groupings comprising each basin were calculated based on their relative base-flow percentages and their relative areas (table 12).

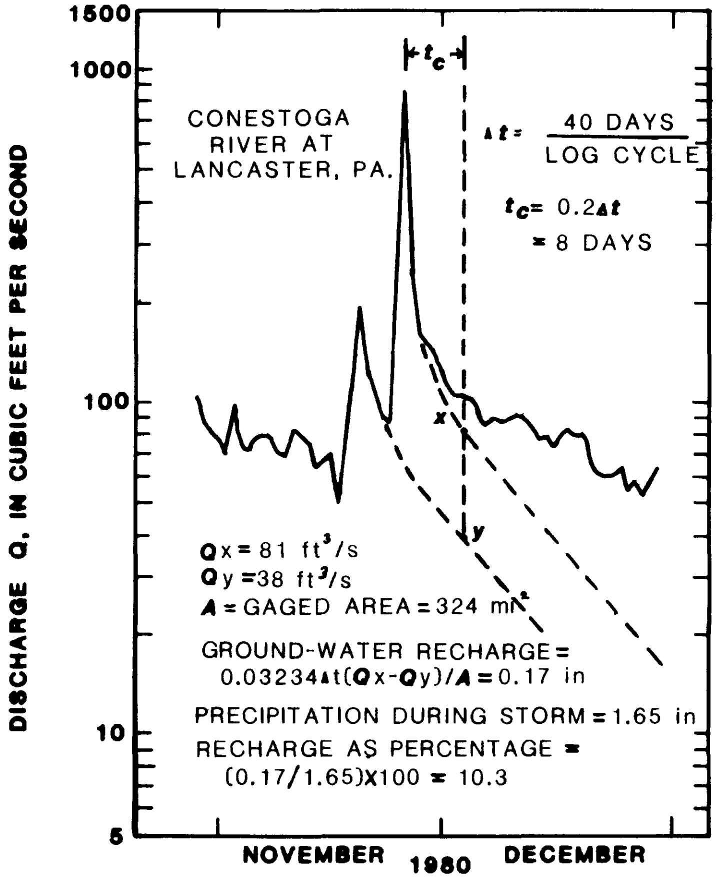


Figure 13.--Example of technique used to estimate recharge from a storm as a percentage of precipitation.

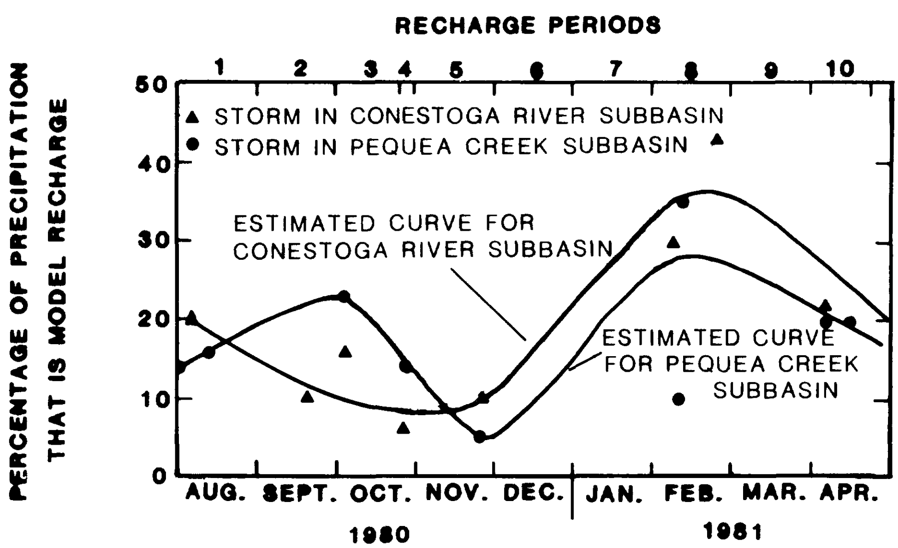


Figure 14.--Proportional distribution of recharge over transient-calibration period for Conestoga River and Pequea Creek subbasins.

Table 12.--Proportional distribution of recharge over transient-calibration period

Formation groupings for transient calibration (unit numbers)	Percentage of precipitation that is recharge									
	August 1980	September 1980	October 1-24, 1980	October 25-31, 1980	November 1980	December 1980	January 1981	February 1981	March 1981	April 1-22, 1981
Stonehenge Formation (1)	32	20	12	11	14	32	57	70	61	50
Ledger, Conestoga Formations (2,3)	25	20	17	12	11	20	37	48	44	34
Epler, Vintage Formations (4,5)	25	16	10	8	11	24	41	51	47	38
Other carbonate rocks (6-11)	20	12	8	7	9	19	32	40	36	28
Metamorphic rocks (12,14)	12	16	15	10	6	7	15	22	19	15
Cocalico Formation (13)	20	12	8	7	9	19	32	40	36	28
Combination of units 3,12 (15)	16	20	20	13	7	8	18	28	25	19
Combination of units 5,11 (16)	22	14	9	7	10	21	36	45	41	33
Combination of units 1,6-11 (17)	26	16	10	9	11	25	44	55	48	39
Triassic sedimentary rocks (18,19,21,22)	14	9	6	5	7	14	23	30	27	21
Diabase (20)	3	2	1	1	2	4	7	8	6	5

Recharge may occur not only from major storms, but also from minor storms. Even though the percentage of precipitation that is recharge may be different for major and minor storms, it was assumed that the assigned percentage for each unit was applicable to the total precipitation. The total precipitation for each of the 10 recharge periods was obtained from NOAA data at seven stations (table 13). The precipitation measured at each station was considered to apply to the area surrounding that station. In this way, 7 precipitation zones were delineated (fig 15).

The initial recharge in each grid block for each recharge period was determined as the product of the average percentage for the appropriate hydrogeologic unit (table 12) and the total precipitation for the appropriate precipitation zone (table 13). Because these recharge amounts were only estimates used to obtain relative proportions of recharge for each recharge period, it was necessary to modify the recharge amounts, so that their sum was equal to the estimated total recharge for the calibration period. Total recharge for the calibration period was estimated as the product of the percentage of precipitation that is recharge during the calibration period for a normal year (discussed in a later section of this report) and the total precipitation observed during the calibration period. As a result, all initial recharge amounts were increased by 50 percent to obtain model recharge. As with steady-state recharge, model recharge is less than actual recharge by consumptive use and by evapotranspiration of ground water.

Specific Yield

Initial Estimates

Initial estimates of specific yield were obtained from a study by Trainer and Watkins (1975) in the upper Potomac River basin, which contains parts of the same physiographic provinces as the modeled area. They recognized three hydrogeologic environments with different specific yields: Fractured rock with thin weathered mantle (0.005); fractured rock with thick weathered mantle (0.01); and carbonate rock with thick weathered mantle and solution-enlarged fractures (0.035). These specific yields are representative of the zone of water-table fluctuation, which may be in weathered mantle or bedrock. The 11 formation groupings were assigned initial estimates of specific yield according to their hydrogeologic environments, as described by Trainer and Watkins (table 14). Triassic and Paleozoic sedimentary units were considered to be fractured rock with thin weathered mantle; metamorphic units were considered to be fractured rock with thick weathered mantle; and carbonate units were considered to be carbonate rock with thick weathered mantle and solution-enlarged fractures.

Adjustments

The initial estimates of specific yield were adjusted in order to obtain agreement between model-generated and observed water-table altitude changes for November 1, 1980 through April 22, 1981 (table 14). The calibration values are greater than the initial estimates; the maximum increase was by a factor of 3 for the Cocalico Formation (unit 13). Specific yields for carbonate units range from 0.060 to 0.090. Triassic units have a value of 0.012; metamorphic units 0.020; and Paleozoic sedimentary units 0.015.

Table 13.--Precipitation for each recharge period of transient calibration

Precipitation zone number	Precipitation station (NOAA)	Precipitation, in inches									
		August 1980	September 1980	October 1-24, 1980	October 25-31, 1980	November 1980	December 1980	January 1981	February 1981	March 1981	April 1-22, 1981
1	York Haven	3.40	2.68	0.55	2.13	2.93	0.52	0.27	5.29	1.41	2.82
2	Landisville 2 NW	2.64	1.67	.93	1.74	3.63	.62	.17	3.86	1.44	3.19
3	Ephrata	2.38	1.66	1.27	1.98	3.51 1/	.89	.42	2.78	1.82	3.92
4	Morgantown	1.80	1.16	1.31	2.63	2.70 1/	.41	.39	4.70	2.33 1/	3.68
5	Lancaster 2 NE FP	1.53	1.44	.93 2/	1.74 2/	3.27	.64	.41	3.31	1.39	3.18
6	Holtwood	3.79	1.02	1.00	1.70	3.26	.62	.17	5.40 2/	1.14	2.63
7	Coatesville 1 SW	2.18	1.62	1.76	2.74	3.14	.61	.42	4.25	1.71	3.17

1/ One storm missing from data; estimated from nearby stations.
2/ No data for period; estimated from nearby stations.

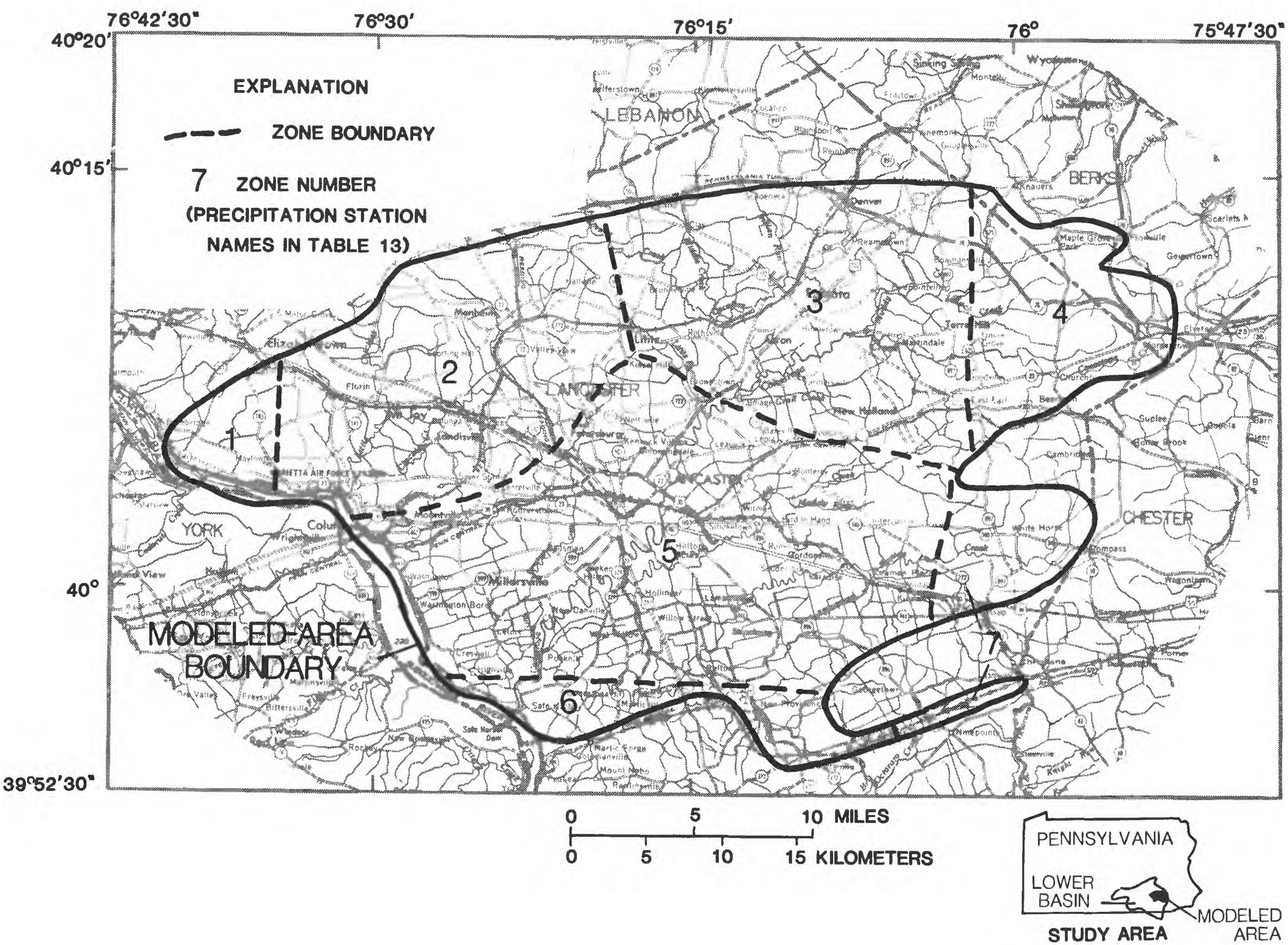


Figure 15.--Precipitation zones used in transient calibration.

Table 14.--Initial estimates of specific yield, and specific yields used in calibrated model

Formation groupings for transient calibration (unit numbers)	Specific yield	
	Initial estimate[1/]	Calibration value
Stonehenge Formation (1)	0.035	0.090
Ledger, Conestoga Formations (2, 3)	.035	.080
Epler, Vintage Formations (4, 5)	.035	.060
Other carbonate rocks (6-11)	.035	.070
Metamorphic rocks (12, 14)	.010	.020
Cocalico Formation (13)	.005	.015
Combination of units 3,12 (15)	.025	.050
Combination of units 5, 11 (16)	.035	.065
Combination of units 1, 6-11 (17)	.035	.080
Triassic sedimentary		
rocks (18, 19, 21, 22)	.005	.012
Diabase (20)	.005	.012

1/ Based on Trainer and Watkins (1975).

Boundary Conditions

During the early stages of the transient calibration, it was determined that the effects of all boundary conditions were significant only immediately adjacent to the boundaries. Because such a small part of the modeled area is adjacent to boundaries, the boundary conditions will have a minimal effect on the results for the entire area or even for individual hydrogeologic units. Therefore, the boundary conditions used in the steady-state calibration (fig.10) also were used in the transient calibration.

Results

Non-parametric statistics--median, 25, and 75 percentiles--were used to determine which specific yields produced the best agreement (table 15). Model-generated changes in water-table altitude were compared to the changes observed between the October 1980 and April 1981 measurements for 5 of the 11 formation groupings. The other six formation groupings did not have enough observations to make a statistical comparison meaningful. The specific yields for these other six groupings were determined by their relation to the specific yields of the five groupings with sufficient observations, as well as the relations between the groupings' model recharges and hydraulic conductivities.

The median water-table altitude changes generated by the model for the five groupings with enough observations are within 1.1 ft of the median observed changes (table 15). However, for all five groupings, the range of model-generated change, as expressed by the difference between the 25 and 75 percentiles, is less than the observed range. The main reason for this is that specific yield was assumed to be uniform within each formation grouping. In reality, specific yield may vary greatly over short distances within a formation grouping due to topography, depth below land surface, differences between individual beds, and other factors. In addition, the specific yield is dependent on whether the water table is located in weathered mantle or bedrock. Therefore, the lack of agreement between ranges of water-table altitude change was accepted as an artifact of the assumption of uniformity.

Sensitivity Analysis

There was an approximate 1:1 relationship between changes in specific yield and resulting changes in water-table altitude. With all other model input variables constant, doubling specific yield halved the median fluctuation of the water table. Similarly, halving specific yield doubled the median fluctuation. This direct relationship was responsible for the sensitivity of the model to specific yield. This sensitivity permitted the precise determination of the specific yields in table 15. However, they are only as accurate as the estimates of model recharge for the 10 recharge periods.

Table 15.--Statistical comparison of observed and model-generated changes in water-table altitude for selected units

Formation groupings for transient calibration (unit numbers)	Water-table altitude change from November 1, 1980 to April 22, 1981, in feet [1/]							
	Observed				Model-generated			
	Number of measurements	Percentiles: 25	Percentiles: Median	Percentiles: 75	Number of grid blocks	Percentiles: 25	Percentiles: Median	Percentiles: 75
Ledger, Conestoga Formations (2, 3)	20	-3.0	-1.1	0.7	1,147	-0.7	0.0	0.5
Epler, Vintage Formations (4, 5)	11	1.1	2.4	6.3	462	1.4	1.9	2.4
Other carbonate rocks (6-11)	15	-.7	.3	2.0	700	.3	.9	1.4
Cocalico Formation (13)	8	3.1	5.1	6.6	359	4.1	5.1	6.1
Triassic sedimentary rocks (18, 19, 21, 22)	5	2.0	6.2	7.0	343	4.6	6.4	8.3

1/ Negative changes indicate decline in water-table altitude.

RELIABILITY OF MODEL RESULTS

The calibrated model can be used to guide the development of ground-water resources in the area. It can provide estimates of the impacts of various ground-water recharge and development schemes on ground-water levels and base flows of streams. It can not provide estimates of site-specific impacts such as drawdown at particular well sites or stream infiltration at particular stream sites.

The model is considered reliable for five reasons:

1. The major controls on ground-water flow were included. Ground-water flow in the area is controlled by secondary permeability, and the distribution of secondary permeability is in turn controlled by lithology and topography. In the model, lithologic variation was approximated by 22 hydrogeologic units and topographic variation was approximated by 5 topographic settings.

2. The general framework of the actual ground-water flow system was approximated. The lateral hydrologic boundaries of the area and the geometric relationships between hydrogeologic units were approximated to about the nearest 1,000 ft (about one-half of a grid-block dimension). The thickness of the zone of active ground-water circulation for each unit and the surface-water drainage system--locations, lengths, altitudes, and areas of streams and lakes--were included in the model.

3. A large data base was available to aid in the quantification of hydrologic characteristics. Physical data for more than 700 wells, daily streamflow data for 6 streams, daily precipitation data for 7 stations, and the results of a previous model study (Gerhart and Lazorchick, 1984) were used to determine water-table altitudes, model recharge, and initial values of hydraulic conductivity, stream leakage coefficients, and specific yield.

4. The regional water-table configuration was reproduced in an average annual steady-state calibration. Reasonable hydraulic conductivities and stream leakage coefficients produced statistical agreement between model-generated and estimated water-table altitudes and base flows.

5. Regional water-table altitude changes were reproduced in a transient calibration. Reasonable specific yields produced statistical agreement between model-generated and observed changes in water-table altitudes.

On the other hand, inherent in the development of the model are the many assumptions that are discussed throughout the report. The following is a summary of the model assumptions:

1. Secondary openings are interconnected at the scale of the analysis.

2. Continuum methods can be used to analyze flow in the interconnected secondary openings.

3. Water-table conditions are found in the upper 150 to 300 ft of the ground-water flow system.

4. Faults do not disrupt ground-water flow at the scale of the analysis.

5. Contacts between units are vertical.

6. Hydrologic characteristics are uniform within units and, in the case of hydraulic conductivity and depth to water table, within topographic setting.

7. There is hydraulic connection between and within all units.

8. The rows and columns of the grid are aligned with the principal directions of hydraulic conductivity.

9. Streambeds are leaky.

10. Stream altitudes are constant in time, preventing any streams from drying up due to base-flow decreases.

11. Model recharge is uniform within major subbasins and units.

12. Ground-water evapotranspiration has no significant effect on model recharge estimates.

13. Current consumptive ground-water use has no significant effect on model recharge estimates.

14. Model boundary conditions are constant in time.

15. Ground-water flow below the zone of active circulation is negligible.

The model was calibrated under natural average conditions (average annual steady-state) and natural transient conditions (November 1, 1980 through April 22, 1981). It was not calibrated under conditions of ground-water withdrawal because withdrawals were not documented in terms of their associated rates of water-table decline. In addition, the specific yields determined in the transient calibration were based on water-table altitude changes for atypical natural transient conditions--a winter and spring when the water table actually declined in some parts of the area. Therefore, when simulating conditions of stress, the model user should be aware that model-generated effects may not be the same as actual effects. However, model-generated water-table declines and base-flow reductions will be general indicators of the relative distribution and magnitude of the effects that would result from imposed stresses.

SUGGESTED USES OF MODEL

The calibrated model can be used to simulate the effects of natural and artificial stresses on the ground-water flow system in the area. The model can be used in steady-state or transient mode. In steady-state mode, the effects simulated are ultimate effects. In transient mode, the effects at any desired time may be simulated.

Natural stresses caused by changes in recharge are variable and intermittent, so transient simulations generally are more appropriate. For example, periods of low recharge, such as droughts, are relatively temporary, and the ground-water flow system would not have the time necessary to reach steady-state conditions under such stresses. Therefore, the ultimate effects obtained from a steady-state simulation would never actually occur. A transient simulation, on the other hand, would show the effects at different stages of a drought, and would be extended only as long as the drought.

Artificial stresses tend to be more long term than natural stresses. For example, major withdrawals of ground water commonly continue for many years at about the same rates, regardless of the natural stress conditions. In fact, most major ground-water withdrawals can be expected to increase. For this reason, steady-state simulations commonly are used to estimate the ultimate effects of artificial stresses. However, transient simulations also are useful, because many withdrawals, such as for irrigation, are intermittent.

Some uses of the model to evaluate the effects of natural stresses are:

1. Transient simulations of hypothetical droughts - simulations to assess the effects of droughts of differing severity and duration;

2. Transient simulations of hypothetical drought recovery - continuations of the simulations above with differing amounts of recharge to estimate recovery times;

3. Transient simulation of current natural effects - an ongoing, updated simulation in which each recharge event is entered as it occurs.

Some uses of the model to evaluate the effects of artificial stresses are:

1. Steady-state simulations of individual, current, continuous withdrawals- simulations to assess the effects of each major continuous withdrawal;

2. Steady-state simulation of all current continuous withdrawals - a simulation to assess the combined effects of all major continuous withdrawals;

3. Transient simulations of individual, current, seasonal withdrawals - simulations to assess the effects of each major seasonal withdrawal;

4. Transient simulation of all current seasonal withdrawals - a simulation to assess the combined effects of all major seasonal withdrawals;

5. Steady-state simulation of an impoundment - a simulation to assess the effects of a major impoundment;

6. Steady-state simulation of urbanization - a simulation to assess the effects of reduced recharge due to urbanization;

7. Transient simulation of current continuous and seasonal withdrawals - an ongoing, updated simulation in which each new major continuous and seasonal withdrawal is entered as it occurs;

8. Steady-state simulations of projected continuous and seasonal withdrawals - simulations to assess the effects of different potential ground-water development schemes.

Simulations can be made that combine any of the natural and artificial stress situations above. Three of the more interesting are:

1. Transient simulations of current continuous and seasonal withdrawals during hypothetical droughts - simulations to assess the combined effects of all current, major, artificial stresses and low-recharge drought conditions of differing severity and duration;

2. Transient simulations of projected continuous and seasonal withdrawals during hypothetical droughts - simulations to assess the combined effects of different potential ground-water development schemes and low-recharge drought conditions of differing severity and duration;

3. Transient simulation of current continuous and seasonal withdrawals under current natural conditions - an ongoing, updated simulation in which the combined effects of current artificial and natural stresses are estimated.

The results of these types of simulations can be used to guide the development of ground-water resources in the area. Such simulations can be used in conjunction with reasonable limits of acceptable base-flow reduction or water-table decline to estimate the optimum amount and distribution of withdrawals.

EXAMPLE SIMULATIONS

General Procedure

The calibrated model was used in transient mode to simulate the effects of four different combinations of natural and artificial stresses. Each simulation began January 1 and continued for two years, ending on December 31. Each consisted of 24 monthly recharge periods with three time steps each. Starting water-table altitudes for each simulation were the average annual altitudes generated in the steady-state calibration. Hydraulic conductivities, stream leakage coefficients, specific yields, and boundary conditions that were determined during the two calibrations were used in the four simulations. Model recharge and ground-water withdrawals were the input variables that were combined to yield the four different sets of conditions.

Graphs showing the generalized stress conditions that were modeled in each of the four simulations are shown in figure 16. Simulation I consists of two consecutive years of normal seasonal conditions. The normal monthly model recharge is higher in winter and spring and lower in summer and fall. The resulting water-table altitudes and base flows are representative of natural aquifer conditions (no ground-water development) during normal climatic years. Simulation I will be used as a basis for comparison for subsequent simulations.

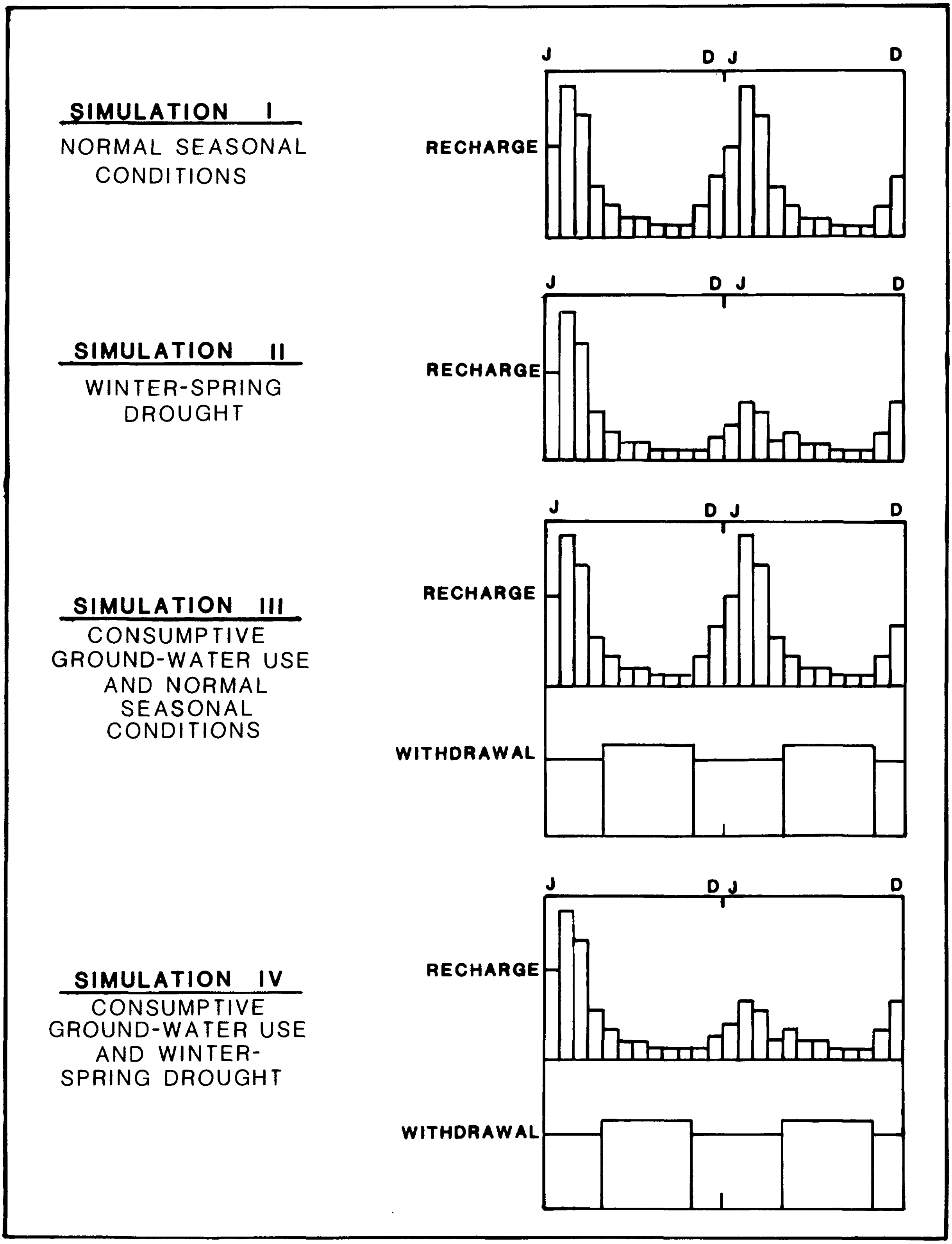


Figure 16.--Generalized model recharge and consumptive ground-water use used in example simulations of stress.

Simulation II includes a hypothetical, 6-month, winter-spring drought. Differences between the water-table altitudes and base flows of this simulation and those of Simulation I are the effects of the drought. The drought begins November 1 of the first year and ends April 30 of the second year. The monthly model recharge is 40 percent of normal, making the hypothetical drought about equal in severity to the actual drought of November 1980 through April 1981. The model recharge for the other months is normal. As in Simulation I, no consumptive ground-water use is included. The resulting water-table altitudes and base flows are representative of natural aquifer conditions during such a drought.

Simulation III consists of normal seasonal conditions (Simulation I) plus consumptive ground-water use. Differences between the water-table altitudes and base flows of this simulation and those of Simulation I are the effects of consumptive use. Ground-water use is 20 percent greater in late spring and early fall. The resulting water-table altitudes and base flows are representative of actual aquifer conditions (current ground-water development) during normal climatic years.

Simulation IV consists of drought conditions (Simulation II) plus consumptive ground-water use (Simulation III). Differences between the water-table altitudes and base flows of this simulation and those of Simulation I are the combined effects of the drought and consumptive use. The resulting water-table altitudes and base flows are representative of aquifer conditions during the actual drought of November 1980 through April 1981.

Simulation of Normal Seasonal Conditions

Before assessing the effects of stresses such as droughts and consumptive ground-water withdrawals, it was necessary to estimate baseline conditions--natural aquifer conditions during normal climatic years (Simulation I). Natural aquifer conditions were simulated by the exclusion of ground-water withdrawals. Normal climatic conditions were simulated by distributing the average annual model recharge over each year of the 2-year period in such a way that the simulated annual high and low water-table altitudes occurred in the spring and fall, respectively.

Years in which average annual precipitation occurs are rare. Also, annual water-table highs and lows rarely occur at the same times from year to year. Because of this, there were no water-level data for a particular year that could be used to define the normal distribution of model recharge. However, for one well in the area (Ln-514), more than 18 years of daily water-level data were available. From a composite of these data, the times of annual water-table high and low were obtained and were assumed to represent those of a normal climatic year (fig. 17). The normal annual high water-table altitude occurs in late March to early April and the normal annual low water-table altitude occurs in late October to early November.

Various distributions of average annual model recharge were entered into the model and 2-year simulations were made until the times of annual high and low water-table altitude for the grid block containing well Ln-514 (block 31-36) were in agreement with the times from the composite hydrograph in figure 17.

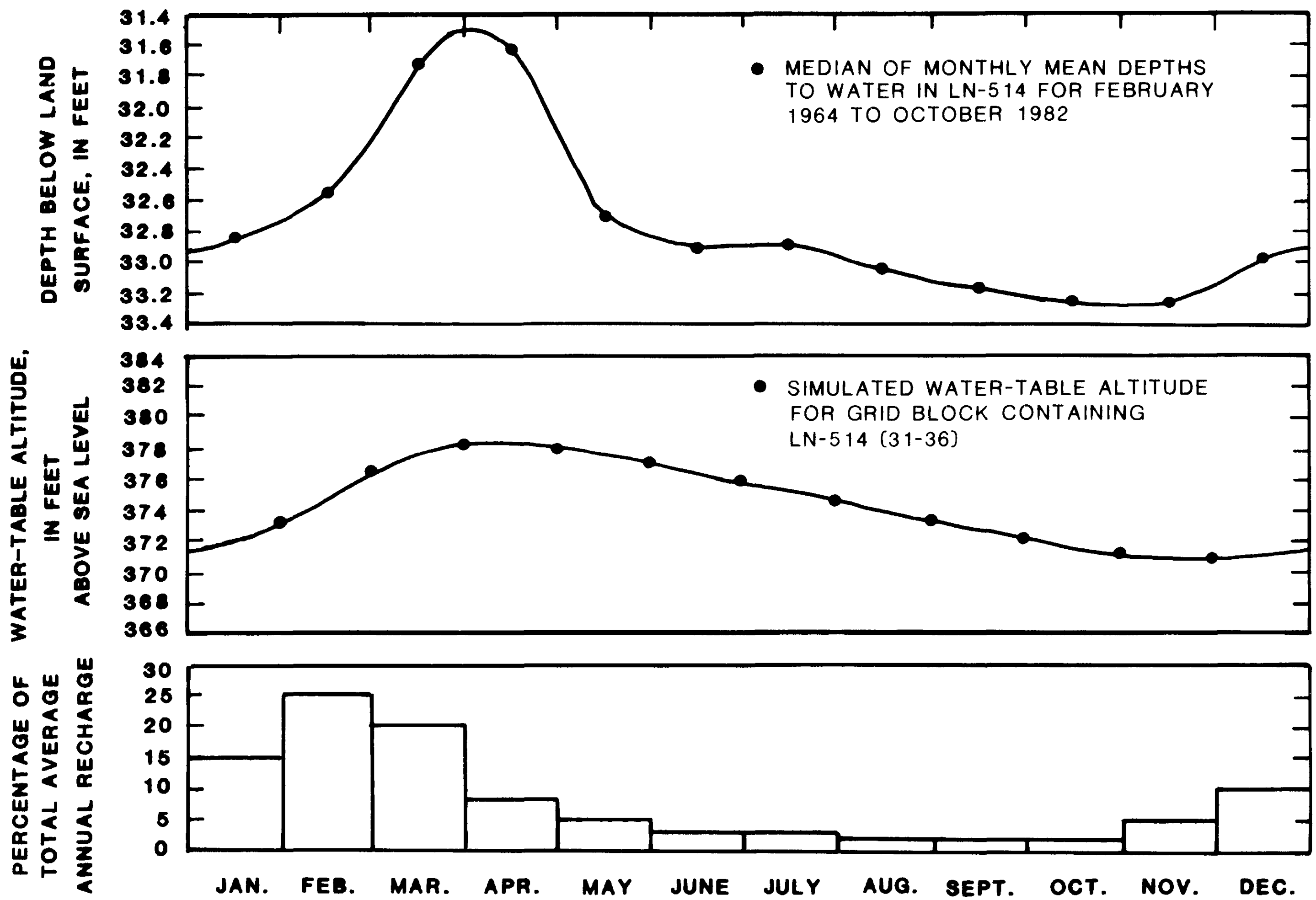


Figure 17.--Normal seasonal water levels in well Ln-514, simulated normal seasonal water-table altitudes for grid block 31-36, and distribution of model recharge during normal year.

The magnitude of the simulated seasonal water-level fluctuation for grid block 31-36 is about 7 ft, whereas the seasonal water-level fluctuation in well Ln-514 is only about 2 ft. This is because the simulated water level represents an average water level over the entire grid block. Well Ln-514 is located in a low topographic setting within grid block 31-36 and is near a stream. Therefore, its water level fluctuates less than water levels for the remainder of the grid block. The simulated water levels also form a much smoother seasonal hydrograph than the composite. This is possibly due to the relatively large (1 month) recharge periods used, or the fact that ground-water evapotranspiration, which could account for the steep decline in water level in April and May in well Ln-514, was not included in the model.

The average annual model recharge for each hydrogeologic unit was distributed over the year according to the above distribution (fig 17). In February, 25 percent of the average annual model recharge occurs; most probably occurs during periods of above-freezing temperatures and warm rains, which cause snow and frozen soil moisture to melt and recharge. On the other hand, only 8 percent of the average annual model recharge occurs from June through August due to high evapotranspiration. A total of 83 percent of the average annual model recharge occurs from November through April.

The results of Simulation I are shown for grid block 26-18 in figure 18. This grid block is in the Epler Formation (unit 4) about 1 mi west of Mt. Joy. It contains a stream reach and a public-supply well owned by the Mt. Joy Borough Authority. This grid block will be used to demonstrate the results of all four example simulations. Water-table altitudes under normal seasonal conditions (Simulation I) are shown for the 2-year simulation period (fig. 18). The annual high water level in March is about 3.5 ft higher than the annual low in October. The base-flow contribution to the stream in this grid block also is shown in figure 18. The base-flow fluctuation parallels the water-level fluctuation. The base-flow contribution is greatest in March (about 1 ft^3/s) and least in October (about 0.5 ft^3/s).

From the overall results of Simulation I, the median annual fluctuation of water level in a normal climatic year is 5.6 ft for carbonate units and 19.4 ft for noncarbonate units. The lowest median fluctuation is 4.6 ft for the Buffalo Springs and Snitz Creek Formations (unit 6); the greatest is 22.4 ft for the Cocalico Formation (unit 13).

Total simulated base flows at the gage sites for five selected streams are shown for March 31 (high flow) and October 31 (low flow) in table 16. For Simulation I, the March 31 base flows range from 64 to 146 percent greater than the October 31 base flows.

Simulation of Winter-Spring Drought

The hypothetical, 6-month, winter-spring drought in Simulation II was implemented in the model by reducing the monthly model recharge by 60 percent for November of the first year through April of the second year. This resulted in about a 50-percent reduction in average annual model recharge.

The results of Simulation II are shown for grid block 26-18 in figure 18. The water-table altitudes and base flows are the same as in Simulation I for

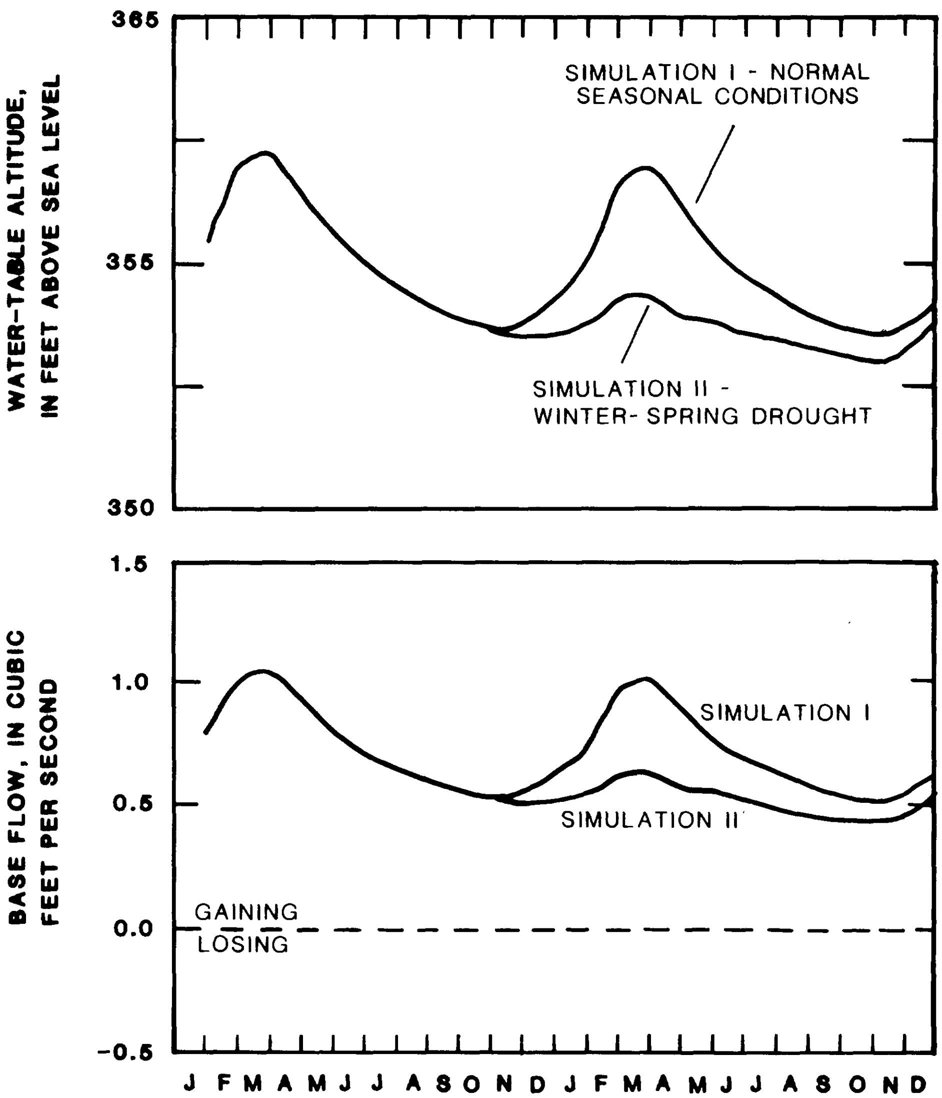


Figure 18.--Simulated water-table altitudes and base flows for grid block 26-18 for Simulations I and II.

the first 10 months. In November, the drought begins and water-table altitude and base flow start to decline from normal seasonal levels and rates. In December, they begin a slight, gradual rise leading to a small peak in February and March. On March 31, the water-table altitude is about 2.5 ft lower than under normal seasonal conditions (Simulation I). Similarly, the base flow on March 31 is about 0.6 ft^3/s, or 40 percent less than under normal seasonal conditions. Water-table altitude and base flow then decline through the rest of the drought, and continue to decline into October because of normally low seasonal recharge. On October 31, 6 months after the drought, the water-table altitude is still about 0.5 ft less than in Simulation I. The base flow is about 0.4 ft^3/s, or still 20 percent less than in Simulation I. Two months later, at the end of the simulation, water-table altitude and base flow are still lower than they were in Simulation I.

On October 31 in Simulation II, 6 months after the drought, the water levels for carbonate units are lower than in Simulation I by a median difference of 3.6 ft; for noncarbonate units, the median difference between the simulations is 8.7 ft. On October 31, the unit with the least residual drought effects is the Stonehenge Formation (unit 1), which has a median difference between Simulations I and II of 0.9 ft; the unit with the greatest residual drought effects consists of the Hammer Creek Formation and the Hammer Creek Conglomerate (unit 22), which has a median difference of 13.7 ft.

The March 31 and October 31 base flows for the five selected streams in table 16 reflect the effects of the hypothetical drought. Because the drought was still underway in March, the effect on base flows is greater in March than it is in the following October. The March 31 base flows in Simulation II are 33 to 51 percent less than they were in Simulation I. In fact, the March 31 base flows are reduced to the point that they are less than normal average annual base flows (table 16). Even on October 31, 6 months after the drought, base flows are still 20 to 37 percent less than they were under normal seasonal conditions.

The residual drought effects on water levels on October 31 of the second year are shown on plate 3 for 18 areas. These areas were selected because they include all reported ground-water withdrawal sites in the area and, therefore, are areas of particular interest during a drought. October 31 was chosen as the date on which to assess the drought effects because, as figure 18 shows, the residual effects of the hypothetical drought, coupled with normally low summer and fall recharge, cause the October 31 water levels to be even lower than water levels at the height of the drought. The conditions under which water levels are lowest are important to ground-water managers in the area because ground-water production from wells in rocks with secondary permeability is very dependent on water level.

The grid blocks in which the reported ground-water withdrawals are located are shown on plate 3. The contours and the numbers in each grid block represent feet of water-level decline caused by the drought. The declines are average declines for the grid blocks. They were obtained by subtracting October 31 water levels in Simulation II from those in Simulation I. It should be emphasized that although the grid blocks in which the ground-water withdrawals are located are shown on plate 3, no ground-water withdrawals were included in

Table 16.--Simulated base flows at gages for selected streams for March 31 and October 31 of second year for example simulations of stress

Stream	Model-generated average annual	Simulated base flow, in cubic feet per second 1/							
		I		II		III		IV	
		Mar.	Oct.	Mar.	Oct.	Mar.	Oct.	Mar.	Oct.
Conestoga River at Lancaster	192.1	306.9	128.6	166.5	101.3	300.9	122.7	161.2	95.4
Pequea Creek at Martic Forge	117.0	156.7	95.8	104.3	76.6	156.7	95.8	104.3	76.6
Little Conestoga Creek at Conestoga Country Club	38.9	58.4	28.3	33.7	22.2	56.4	26.3	32.0	20.4
Little Conestoga Creek at East Petersburg	13.6	21.5	9.2	11.3	7.2	21.5	9.1	11.2	7.1
Chickies Creek at Manheim	10.8	17.2	7.0	8.5	4.4	16.0	5.8	7.4	3.2

1/ Base flow is only for those parts of stream basins in modeled area.

the simulations used to determine the declines shown; the drought effects shown are based on natural aquifer conditions.

The effect of the hypothetical drought generally is about 5 ft of water-level decline for the 15 selected areas that are underlain mainly by carbonate units. The two elongated areas in the northeastern corner and the small area in the southwestern corner of the model area are underlain mainly by Triassic sedimentary units and metamorphic units, respectively. Water-level declines for the Triassic sedimentary areas are as high as 20 ft (on the ridge just east of Ephrata). The declines for the metamorphic area are slightly greater than 10 ft.

Simulation of Consumptive Ground-Water Use and Normal Seasonal Conditions

In Simulation III, the effects of consumptive ground-water use were assessed under normal seasonal conditions. The monthly model recharge rates from Simulation I were used and estimated monthly ground-water withdrawal rates were entered for those grid blocks in which withdrawal wells are located. There were 52 grid blocks with ground-water withdrawals, and they were grouped into the 18 areas previously shown.

Ground-water use data for the area were provided by the Pennsylvania Department of Environmental Resources. They were obtained from questionnaires sent to ground-water users from 1972 through 1979. Ground-water users reporting annual withdrawals greater than 1 Mgal were included. There were five types of use included: Agricultural irrigation, quarry dewatering, municipal supply, industrial supply, and golf-course irrigation. The locations of the withdrawals are shown on plate 2 and their rates of withdrawal are shown in table 17. All ground-water use was assumed to be 100-percent consumptive--that is, lost from the ground-water system. For lack of more current ground-water use data, the withdrawal rates reported for 1972-79 were used in the model as approximations of current rates.

Agricultural irrigation users were inventoried in 1977; only three used over 1 Mgal (table 17). Their combined ground-water withdrawal rate was only about 0.2 Mgal/d. Because their use of ground water was for crop irrigation, their total annual withdrawals were converted to daily withdrawal rates by dividing them by the number of days in the irrigation season, which was assumed to be 184 (May 1 to October 31). No agricultural irrigation withdrawals were entered in the model for November 1 through April 30.

From an inventory conducted in 1978, six quarries were withdrawing more than 1 Mgal of ground water annually for dewatering purposes (table 17). Together, they withdrew nearly 1.4 Mgal/d. Daily withdrawal rates were determined from the reported number of days of operation for each quarry. The quarries were assumed to be operating every day between May 1 and October 31; the remaining days of reported operation were used to determine withdrawal rates for November 1 through April 30.

Table 17.--Reported ground-water use data and withdrawals used in Simulations III and IV

[Withdrawal use codes: A, agricultural irrigation; Q, quarry dewatering; M, municipal supply; I, industrial supply; G, golf-course irrigation]

Withdrawal site1/	Grid block	Ground-water user	Number of wells	Year of inventory	Reported average annual withdrawal rate, in gallons per day	Estimated November to April withdrawal rate, in gallons per day	Estimated May to October withdrawal rate, in gallons per day
A_1	17-40	Noah Kreider	1	1977	124,970	--	247,910
A_2	24-46	Glenn Thomas	1	1977	17,860	--	35,420
A_3	49-35	Clyde Eshelman	1	1977	14,140	--	28,040
Q_1	3-62	Lancaster Lime and Stone Corp.	-	1978	16,140	11,800	20,400
Q_2	26-41	Binkley and Ober, Inc.	-	1978	26,580	15,940	37,040
Q_3	28-55	D.M. Stoltzfus and Son, Inc.	-	1978	88,490	62,460	114,100
Q_4	18-71	David M. Burkholder, Inc.	-	1978	1,152,000	1,064,750	1,237,830
Q_5	21-77	Martin Limestone, Inc.	-	1978	11,540	11,450	11,630
Q_6	44-43	H.R. Miller, Inc.	-	1978	102,050	59,610	143,810
M_1	4-74	East Cocalico Township Authority	2	1979	110,000	99,920	119,910
M_2	8-69	do	1	1979	11,000	9,990	11,990
M_3	8-71	do	1	1979	35,000	31,790	38,150
M_4	9-69	do	1	1979	75,000	68,130	81,760
M_5	10-69	do	1	1979	50,000	45,420	54,500
M_6	10-70	do	1	1979	30,000	27,250	32,700
M_7	15-37	Northwestern Lancaster County Authority	1	1979	72,000	65,400	78,490
M_8	18-46	Lititz Borough Water Works	4	1977	737,450	669,910	803,900
M_9	18-48	do	2	1977	730,100	663,230	795,870
M_{10}	17-61	Akron Borough Municipal Water Works	5	1979	400,000	363,360	436,040
M_{11}	16-77	Terre Hill Borough Water Department	1	1979	16,580	15,060	18,070
M_{12}	17-76	do	2	1979	9,720	8,830	10,590
M_{13}	17-78	do	1	1979	32,280	29,320	35,190
M_{14}	26-18	Mt. Joy Borough Authority	1	1979	468,000	425,140	510,160
M_{15}	26-19	do	1	1979	612,000	555,950	667,140
M_{16}	30-34	East Hempfield Township Municipal Authority	1	1979	300,000	272,520	327,030
M_{17}	33-34	do	3	1979	1,150,000	1,044,670	1,253,610
M_{18}	30-59	Leola Water Authority	1	1979	150,000	136,260	163,510
M_{19}	31-61	do	3	1979	260,000	236,190	283,420

Table 17.--Reported ground-water use data and withdrawals used in Simulations III and IV (continued)

[Withdrawal use codes: A, agricultural irrigation; Q, quarry dewatering; M, municipal supply; I, industrial supply; G, golf-course irrigation]

Withdrawal site	Grid block	Ground-water user	Number of wells	Year of inventory	Reported average annual withdrawal rate, in gallons per day	Estimated November to April withdrawal rate, in gallons per day	Estimated May to October withdrawal rate, in gallons per day
M_{20}	29-69	Western Heights Water Authority	1	1979	6,650	6,040	7,250
M_{21}	29-70	do	2	1979	3,830	3,480	4,170
M_{22}	27-71	New Holland Borough Water Department	1	1979	5,850	5,310	6,380
M_{23}	25-77	Blue Ball Water Authority	3	1979	92,160	83,730	100,470
M_{24}	34-75	Acorn Water Works	1	1979	3,300	3,000	3,600
M_{25}	45-40	Millersville Municipal Water Authority	5	1979	353,150	320,800	384,950
M_{26}	47-40	Millersville State College	1	1978	79,530	72,250	86,700
I_1	17-37	Raybestos-Manhattan, Inc.	3	1977	747,950	679,450	815,340
I_2	18-37	Fuller Co.	1	1977	82,190	74,660	89,590
I_3	18-47	Wilbur Chocolate Co., Inc.	2	1977	600,000	545,050	654,060
I_4	16-66	Spring Glen Farm Kitchen, Inc.	2	1977	27,400	24,890	29,870
I_5	21-77	Martin Limestone, Inc.	6	1977	13,700	12,450	14,930
I_6	26-21	Peter Paul, Inc.	1	1977	28,360	25,760	30,920
I_7	34-33	Musser's Potato Chips, Inc.	3	1977	32,880	29,870	35,840
I_8	32-43	National Bearings Co.	1	1977	10,580	9,610	11,530
I_9	33-43	Howmet Aluminum Corp.	2	1977	84,620	76,870	92,240
I_{10}	30-62	Dart Container Corp.	3	1977	139,730	126,930	152,320
I_{11}	29-73	Victor F. Weaver, Inc.	4	1977	569,860	517,670	621,200
I_{12}	27-76	New Holland Concrete Div., Martin Limestone, Inc.	1	1977	17,810	16,180	19,410
I_{13}	35-13	Armstrong Cork Co., Marietta Carpet Plant	2	1977	428,350	389,120	466,940
I_{14}	36-14	Armstrong Cork Co., Marietta Ceiling Plant	1	1977	151,230	137,380	164,860
I_{15}	53-30	Turkey Hill Dairy and Supper Bell Foods	4	1977	27,070	24,590	29,510
I_{16}	47-54	General Battery Corp.	1	1977	19,570	17,780	21,330
I_{17}	39-61	Empire Kosher Poultry, Inc.	4	1977	400,000	363,360	436,040
G_1	42-58	Host Farm Resort	5	1972	125,000	--	250,000
				Totals	10,853,670	9,560,580	12,127,660

1/ Withdrawal site locations on Plate 2.

From inventories conducted from 1977 through 1979, 14 municipalities were withdrawing ground water from 26 different grid blocks (table 17). Each municipality was using from one to seven wells; where more than one well was located in a grid block, their withdrawal rates were added. Total municipal-supply use was about 5.8 Mgal/d. Based on reported peak-use data, withdrawal rates for May 1 to October 31 were increased to be 20 percent greater than the rates for the rest of the year. The increase in ground-water use for municipal supply can be seen by comparing the 1965 total of about 1 Mgal/d for carbonate rocks of the Lancaster 15-minute quadrangle (Meisler and Becher, 1971) with the reported total of about 3.4 Mgal/d for the same area in 1977-79.

Industrial ground-water use was inventoried in 1977; 17 industries withdrew more than 1 Mgal annually from one to six wells (table 17). The combined industrial use was about 3.4 Mgal/d. As with municipal-supply use, May 1-October 31 withdrawal rates were increased to 20 percent greater than the rates during the rest of the year. The increase in industrial use between 1965 and 1977 for carbonate rocks of the Lancaster 15-minute quadrangle is not as dramatic as that for municipal-supply use. In 1965, about 0.9 Mgal/d was withdrawn (Meisler and Becher, 1971); about 1.6 Mgal/d was withdrawn in 1977.

According to an inventory conducted in 1972, only one golf course used more than 1 Mgal (table 17). Its average withdrawal rate was only about 0.1 Mgal/d, but because the ground water was used for irrigation, the withdrawal rate used in the model was determined by assuming that the total annual withdrawal occurred only from May 1 to October 31. No irrigation withdrawals for golf courses were entered in the model for other months.

The total annual withdrawal rate for all five uses is 10.9 Mgal/d (table 17). The total rate for November 1 through April 30 is 9.6 Mgal/d; the total rate for May 1 through October 31 is 12.1 Mgal/d. About 93 percent of the ground water withdrawn, or 10.1 Mgal/d, is withdrawn from carbonate units.

The results of Simulation III, which included the above ground-water withdrawals, are shown for grid block 26-18 in figure 19. The water-table altitude and base flow in Simulation III follow the same trend as in Simulation I; however, they are lower because of withdrawal from the Mt. Joy municipal-supply well. During the summer and fall, the water-table altitude and base flow in Simulation III are farther below those of Simulation I than they are during the winter and spring. This is the result of the 20-percent increase in municipal-supply withdrawal rate from May 1 to October 31. The water-table altitude is lower by about 3 to 4 ft as a result of the withdrawal. The March 31 base flow in Simulation III is about 45 percent less than in Simulation I. The base-flow contribution to the stream in the grid block ceases in September and resumes at the end of November. During the interim months, the reach of stream is shown as losing water to the aquifer at a maximum rate of about 0.05 ft^3/s.

The March 31 and October 31 base flows for the five selected streams discussed previously are less than in Simulation I by the amount of ground water being withdrawn from each stream basin (table 16). The base flow for

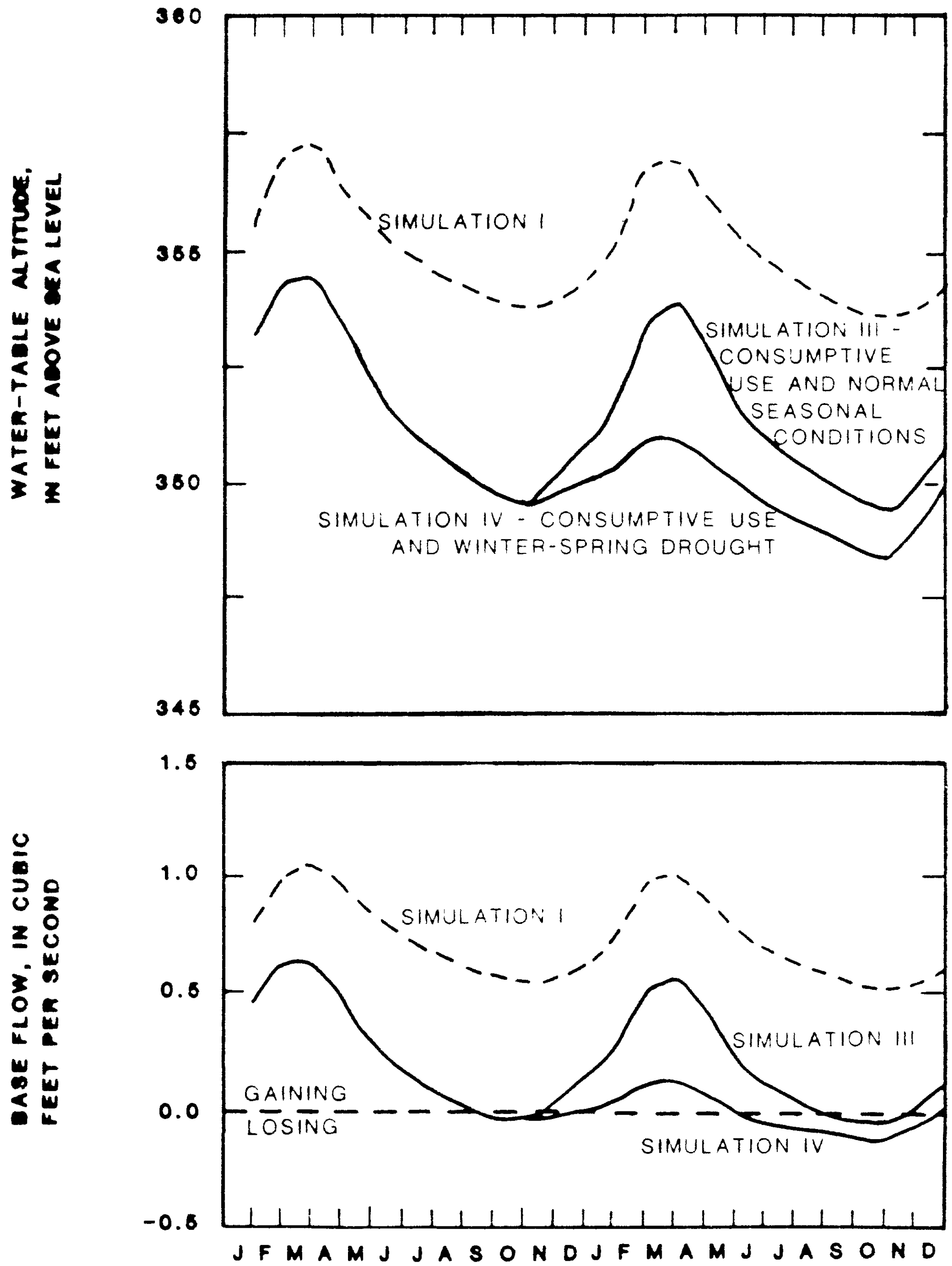


Figure 19.--Simulated water-table altitudes and base flows for grid block 26-18 for Simulations III and IV.

the Conestoga River above the gage at Lancaster shows the greatest reduction (about 6 ft^3/s or 3.9 Mgal/d). On the other hand, because there are no ground-water withdrawals in the part of the Pequea Creek basin that is in the modeled area, there is no difference in base flow between Simulation III and Simulation I. It is probable that although ground water withdrawn from the aquifer reduces base flow, the total streamflow does not decrease much because most of the ground water withdrawn for quarry dewatering, municipal supply, and industrial supply probably is eventually discharged to streams in the same basin from which it is withdrawn.

The declines in water-table altitude on October 31 that were caused by withdrawals of ground water in Simulation III are shown on plate 4. The declines are centered around withdrawal sites and represent average declines for the grid blocks. They were obtained by subtracting October 31 water-table altitudes in Simulation III from those in Simulation I and, therefore, represent drawdowns due to withdrawals under normal seasonal conditions. The drawdowns for the grid blocks that contain withdrawal sites range from 0.1 to 33 ft for the 16 areas that are underlain mainly by carbonate and metamorphic units (plate 4). Drawdowns greater than 10 ft are limited to the grid blocks that contain withdrawal sites, with the exception of two grid blocks adjacent to grid block 33-34, where more than 1 Mgal/d is being withdrawn from carbonate rocks by three wells owned by the East Hempfield Township Municipal Authority. Drawdowns greater than 5 ft are found no farther than one grid block, or about 2,000 to 2,500 ft, away from withdrawal sites.

The drawdowns for the grid blocks containing withdrawal sites and underlain mainly by Triassic sedimentary units range from 3 to 79 ft (plate 4). Drawdowns greater than 10 and 5 ft generally are found no farther from withdrawal sites than they are for carbonate and metamorphic units. However, the drawdowns associated with one grid block (17-61) are much greater in and adjacent to the withdrawal site and extend farther from the site. At this site, five wells operated by the Akron Borough Municipal Water Works are withdrawing about 0.4 Mgal/d from the New Oxford Formation (unit 21) southwest of Ephrata. This results in 79 ft of drawdown for the grid block containing the wells. A drawdown of 28 ft occurs in the grid block adjacent to and east of the withdrawal site. Drawdowns greater than 10 and 5 ft extend up to about 3,700 ft and 1 mi, respectively, from the withdrawal site. Thus, the cone of depression caused by the withdrawals is more extensive than those around other withdrawal sites in Triassic sedimentary units, and it also is substantially deeper and steeper. The surface trace of the cone of depression is an ellipse with its major axis aligned in an east-west direction. This is because the New Oxford Formation is anisotropic; modeled hydraulic conductivity in the east-west direction is 5 times that in the north-south direction.

The main reason for the more severe drawdown effects near grid block 17-61 is that all five Akron Borough wells are located in the same grid block. Several miles northeast of grid block 17-61, five wells operated by the East Cocalico Township Authority in similar hydrogeologic units, and withdrawing about 50 percent less ground water than the five wells in grid block 17-61, cause about 85 percent less drawdown. These five wells are located in five different grid blocks, resulting in significantly less interference of the cones of depression.

Simulation of Consumptive Ground-Water Use and Winter-Spring Drought

Simulation IV combined consumptive ground-water use (Simulation III) with the hypothetical, 6-month, winter-spring drought (Simulation II), a combination that approximated the conditions of the 1980-81 drought. On March 31, the water-table altitude is about 6 ft lower in grid block 26-18 than under natural aquifer and normal seasonal conditions (fig 19). On October 31, it is about 5 ft lower. The base flow in the block on March 31 is about 0.15 ft^3/s, or about 85 percent less than in Simulation I. The base-flow contribution ceases in June and does not resume until December. The stream reach is losing water during that 6-month period, reaching a maximum rate of loss of more than 0.1 ft^3/s in October.

The relationship between water-table altitudes of Simulation IV and those of Simulation III (fig. 19) is nearly the same as between water-table altitudes of Simulations II and I (fig. 18)--that is, the effects of the hypothetical drought are nearly the same whether imposed on actual aquifer conditions of reported withdrawal or natural aquifer conditions of no withdrawal. Actually, however, the difference in water-table altitude between Simulations IV and III is slightly greater than the difference between Simulations II and I. Under unconfined aquifer conditions, the effects of a stress are greater as saturated aquifer thickness decreases. Because the withdrawal lowered the water-table altitude by 3 to 4 ft, the hypothetical drought of Simulation IV was imposed on an aquifer with 3 to 4 ft less saturated thickness, resulting in slightly greater declines in water-table altitude. However, because the total saturated aquifer thickness for grid block 26-18 was about 295 ft, the additional effect caused by imposing the drought on withdrawal conditions rather than on natural unstressed conditions was minor. In some cases, as will be shown later, this additional effect was substantial.

The March 31 and October 31 base flows for the five selected streams (table 16) are slightly less than they were in Simulation II, except in Pequea Creek, where they are the same because there are no ground-water withdrawals in that basin. However, there are no additional decreases due to the combination of withdrawals and hypothetical drought. In fact, the decrease in base flows in Simulation IV is less than the sum of the decreases in Simulations II and III. For example, on March 31 for the Conestoga River above Lancaster, the effect of the hypothetical drought alone (Simulation II) is a decrease in base flow of 140.4 ft^3/s. The effect of ground-water withdrawals alone (Simulation III) is a decrease in base flow of 6 ft^3/s. When the two stresses are combined (Simulation IV), the total decrease in base flow might be expected to be greater than the sum of the two separate decreases (146.4 ft^3/s). However, the decrease in Simulation IV is only 145.7 ft^3/s. The reason for this apparent discrepancy involves the stream-discharge cutoff altitude for those grid blocks that contain streams and are near ground-water withdrawal sites. When the water-table altitude for such a grid block is above the cutoff altitude, base flow will decrease in direct proportion to decreases in water-table altitude. When the water-table altitude drops below the cutoff altitude, however, base flow will not decrease with further decreases in water-table altitude. In such a grid block where a withdrawal (Simulation III) caused the water-table altitude to drop below the cutoff altitude, imposition of the hypothetical drought in Simulation IV does not cause any further base-flow reduction. Without the withdrawal (Simulation II), however, the water-table altitude may be above the cutoff altitude, allowing the drought to cause a decrease in base flow. Thus, for such grid blocks, the effect of the hypothetical drought is less when combined with the effect of withdrawals than when imposed on natural aquifer conditions with no withdrawals.

The declines in water-table altitude on October 31 that were caused by the combination of hypothetical drought and consumptive ground-water withdrawals are shown on plate 5 for the 18 areas. The declines were obtained by subtracting October 31 water-table altitudes in Simulation IV from those in Simulation I, and are representative of differences between natural aquifer conditions under normal seasonal conditions and actual aquifer conditions during the actual drought of 1980-81.

The declines for the grid blocks that contain withdrawal sites and are underlain mainly by carbonate and metamorphic units range from 0.6 to 38 ft (plate 5). An additional decline due to the combination of withdrawal and hypothetical drought occurs for many of these grid blocks. For example, for grid block 33-34, the drought alone causes 1 ft of decline (plate 3), the ground-water withdrawal alone causes 33 ft of decline (plate 4), and the combination of the two stresses causes 38 ft of decline (plate 5). An additional decline of 4 ft results from the combination. Because this additional decline occurs mainly for the grid blocks containing withdrawal sites, most declines for areas surrounding withdrawal sites are simply the sum of the declines in Simulations II and III.

The declines for the grid blocks containing withdrawal sites and underlain mainly by Triassic sedimentary units range from 7 to 109 ft (plate 5). Because the declines in water-table altitude due to ground-water withdrawals (Simulation III) are greater for these units than for carbonate and metamorphic units, the additional declines due to combination with the hypothetical drought also are greater. For example, for grid block 17-61, in which the five wells operated by the Akron Borough Municipal Water Works are located, the additional decline is 24 ft. Accordingly, the additional declines occur at greater distances from withdrawal sites than for carbonate and metamorphic units. Therefore, for much of the two Triassic sedimentary areas, the declines are greater than the sum of the declines in Simulations II and III.

No quantitative data were available to evaluate the agreement of the model-generated drought effects in Simulation IV with actual water-level declines that occurred during the drought of 1980-81. However, the timing and duration of periods of mandatory water-conservation restrictions that were imposed by three municipalities provide a qualitative verification. Information concerning the restrictions in Akron, East Cocalico, and Terre Hill was obtained from the Pennsylvania Department of Environmental Resources (Runkle, oral commun., 1982). All three municipalities are supplied by ground water from Triassic sedimentary units, the units for which the greatest overall simulated declines due to hypothetical drought occur (plate 3).

The first municipality to impose mandatory water-conservation restrictions was Akron, whose wells are located in grid block 17-61, which has the greatest simulated decline in water-table altitude of any grid block (plate 5). Three of Akron's five wells experienced severe drawdown problems during 1981 and Akron was under restrictions for about 10 months. The next municipality to impose such restrictions was East Cocalico, with two wells located in grid block 4-74 and five other wells located in separate grid blocks about 2 mi southwest of grid block 4-74. Grid block 4-74 has the second greatest simulated decline in water-table altitude (plate 5). The simulated declines for the other five grid blocks where East Cocalico operates wells range from 7 to 34 ft. East Cocalico was on restrictions for nearly 4 months. The third municipality to impose mandatory water-conservation restrictions was Terre Hill. It operates four wells in three adjacent grid blocks, which have simulated declines ranging from 13 to 29 ft (plate 5). Water use in Terre Hill was restricted for nearly 6 months.

SUMMARY

Ground water in a 626-mi^2 area in Lancaster and Berks Counties is present under unconfined conditions in bedrock and overlying weathered mantle. In the bedrock, ground-water flow is controlled by secondary permeability. Secondary openings, enlarged by weathering and solution, are the avenues for the flow of most ground water. The number, size, and interconnection of secondary openings differ with lithology, depth, and topography.

The ground-water flow system is recharged by infiltration of precipitation. Recharge occurs nearly everywhere; virtually all discharge occurs in stream valleys. Local flow systems dominate, with ground water discharging in valleys adjacent to its area of recharge. Depth to the water table ranges from zero at streams to 100 ft under hilltops. For intermediate topographic settings, the water table generally is 15 to 60 ft below land surface.

The area was subdivided into 22 hydrogeologic units based on lithologic and hydrologic differences. The units range in area from about 2 to 124 mi^2. Most units consist of a single geologic formation. The major units were categorized as either carbonate rocks, Triassic sedimentary rocks, metamorphic rocks, or Paleozoic sedimentary rocks. The depth to the water table, model recharge amounts, and hydrologic characteristics differ between units. Aquifer thickness also differs between units and ranges from 150 to 300 ft.

The three-dimensional ground-water flow model of Trescott (1975) and Trescott and Larson (1976) was modified and used in two-dimensional mode. A finite-difference grid consisting of rectangular blocks (2,015 x 2,332 ft) was superimposed on the area. Each hydrogeologic unit consists of a number of grid blocks proportional to its area. Hydrologic characteristics were assumed uniform within each grid block. Ground-water flow components included in the model were recharge, discharge to streams, infiltration from streams, boundary flow, change in storage, flow between adjacent units, and withdrawal from wells (in example simulations).

The model was calibrated under average annual steady-state conditions. The water-table altitude for each grid block was estimated by subtracting the average annual depth to water from the average land-surface altitude. Average annual stream altitudes were used. Constant-flux boundaries were placed around the edges of the area, except in the northeastern corner where no-flow boundaries were used and along the Susquehanna River where constant-head boundaries were used. The average annual model recharge was estimated by separating base flow from runoff on streamflow hydrographs. Initial estimates of hydraulic conductivity and stream leakage coefficients for each unit were adjusted until satisfactory agreement was achieved between model-generated and estimated water-table altitudes. Non-parametric statistics were used to assess the calibration. The median differences between model-generated and estimated water-table altitudes for all units were less than 8 ft. For carbonate units, 80 percent of the differences were less than 22 ft. For non-carbonate units, 80 percent were less than about 40 ft. Model-generated base flows for six streams were compared to base flows estimated from hydrographs. All were within 13 percent of the estimated base flows; five were within 6 percent.

Hydraulic conductivity was varied within each unit according to the dominant topographic setting for each grid block. Valley-bottom blocks were assigned the highest and hilltop blocks the lowest hydraulic conductivities. Hydraulic conductivities resulting from the steady-state calibration range from 0.01 ft/d under hilltops in diabase to 1,048 ft/d under valley bottoms in the Stonehenge Formation. Carbonate units have the highest average hydraulic conductivity (8.8 ft/d); metamorphic units have the lowest (0.5 ft/d).

Two stream leakage coefficients were determined for each unit--one for gaining-stream conditions and the other for losing-stream conditions. Gaining-stream leakage coefficients range from 0.021 ft/d for the Wissahickon Formation and diabase to 16.805 ft/d for the Richland Formation. Carbonate units have the highest average gaining-stream leakage coefficient (1.83 ft/d); Paleozoic sedimentary units have the lowest (0.11 ft/d). Losing-stream leakage coefficients are 50 percent of gaining-stream leakage coefficients for carbonate units and 10 percent for most of the other units.

The average annual model recharge (from precipitation) is about 372 Mgal/d. Ground-water flow across model boundaries contributes about 4 Mgal/d and another 12 Mgal/d is derived from infiltration from streams, bringing the overall amount of average annual recharge to about 388 Mgal/d. Carbonate units receive the greatest overall average annual recharge, 1.14 (Mgal/d)/mi^2; metamorphic units receive the least, 0.47 (Mgal/d)/mi^2.

Of the three major input variables, the model is most sensitive to model recharge, followed by hydraulic conductivity and gaining-stream leakage coefficient. Metamorphic units are generally most sensitive to changes in all variables; carbonate units are least sensitive.

The model was calibrated under transient conditions for November 1, 1980 through April 22, 1981. Hydraulic conductivities, stream leakage coefficients, and boundary conditions from the steady-state calibration were used. Model recharge was determined by using streamflow hydrographs for major storms during the period. Initial estimates of specific yield were adjusted until satisfactory agreement was achieved between model-generated and observed changes in water-table altitude. Non-parametric statistics were used to assess the calibration. The median model-generated and observed water-table changes were within 1.1 ft for those units with at least 5 observations. The range of water-table change generated by the model was less than observed. Specific yields resulting from the transient calibration range from 0.06 to 0.09 for carbonate units. Metamorphic, Paleozoic sedimentary, and Triassic units have specific yields of 0.02, 0.015, and 0.012, respectively.

The calibrated model was used in transient mode to simulate the effects of four different combinations of natural and artificial stresses. Normal seasonal conditions were simulated in Simulation I. Water-table altitudes were highest in March and lowest in October and the median annual fluctuation was 5.6 ft for carbonate units and 19.4 ft for noncarbonate units. Similarly, base flows were greatest in March and least in October.

In Simulation II, the effects of a hypothetical drought were simulated. In October (6 months after the drought), the median water-table decline caused by the drought was 3.6 ft for carbonate units and 8.7 ft for noncarbonate units. Base flows in October were still significantly affected by the drought.

In Simulation III, drawdowns caused by reported ground-water withdrawals totaling 10.9 Mgal/d were simulated. October drawdowns for those grid blocks that contain withdrawal sites ranged from 0.1 to 33 ft for 16 selected carbonate and metamorphic areas and from 3 to 79 ft for two selected Triassic sedimentary areas. Base flows in October were reduced by withdrawal amounts.

In Simulation IV, the combined effects of hypothetical drought and reported ground-water withdrawals were simulated, resulting in conditions similar to the 1980-81 drought. Water-table declines in October ranged from 0.6 to 38 ft for the selected carbonate and metamorphic areas and from 7 to 109 ft for the selected Triassic sedimentary areas. Additional declines caused by dewatering when the drought and withdrawals were combined were as much as 24 ft. The three municipalities that imposed mandatory water-conservation restrictions during the 1980-81 drought are located in Triassic sedimentary areas and had simulated declines that were in the same general relation to each other as the dates on which the restrictions were imposed. October base flows were reduced by amounts slightly less than the sum of the reductions caused separately by drought and withdrawals.

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SUPPLEMENT I

Water-level measurement data from observation-well network

The following table contains the results of water-level measurements in 68 wells (plate 2) in the modeled area in October 1980 and April 1981. The change in water level also is included; a negative change indicates a decline in water level. In addition, the hydrogeologic unit and the grid block in which each well is located are given. All wells are in Lancaster County.

			October 1980		April 1981		
Local well number	Grid block	Hydrogeologic unit	Day	Depth below land surface, in feet	Day	Depth below land surface, in feet	Change in water level, in feet, from October 1980 to April 1981
514	31-36	5	29	33.37	22	33.16	0.21
521	39-37	3	30	9.88	22	7.56	2.32
538	42-32	3	30	67.91	22	70.72	- 2.81
564	45-37	3	30	48.97	21	50.66	- 1.69
691	34-30	8	30	34.78	22	34.96	- .18
725	35-53	2	29	20.40	20	15.76	4.64
797	29-39	8	29	22.52	20	20.51	2.01
920	26-45	6	29	27.25	20	26.10	1.15
938	22-31	4	29	48.01	20	46.31	1.70
1036	23-40	4	30	21.44	21	19.05	2.39
1063	9-51	4	28	46.43	21	46.49	- .06
1075	14-43	4	28	57.19	21	55.16	2.03
1107	17-52	9	30	42.36	21	38.23	4.13
1413	62-73	3	28	62.52	20	69.19	- 6.67
1425	48-30	3	29	33.00	22	37.40	- 4.40
1426	50-41	3	29	20.94	22	20.70	.24
1427	61-42	3	29	32.15	22	34.28	- 2.13
1429	52-48	3	29	32.83	21	31.02	1.81
1430	50-56	3	29	27.02	22	20.32	6.70
1431	40-86	2	28	59.64	20	61.67	- 2.03
1434	53-62	15	29	32.50	21	34.33	- 1.83
1435	36-41	11	30	26.12	20	24.98	1.14
1436	21-37	4	29	52.96	20	37.65	15.31
1437	21-34	4	30	39.98	20	33.70	6.28
1438	14-35	13	30	26.79	20	19.85	6.94
1440	17-26	13	29	19.86	20	16.19	3.67
1441	11-86	18	29	58.37	21	55.87	2.50
1444	37-80	2	29	19.92	20	20.36	- .44
1445	44-78	11	28	79.46	20	80.15	- .69
1446	15-61	13	30	68.34	22	62.56	5.78
1449	12-55	7	30	10.68	22	9.88	.80
1450	20-56	13	30	34.47	22	34.85	- .38
1453	43-72	2	28	26.84	20	31.64	- 4.80
1454	34-71	8	30	27.94	21	28.15	- .21
1455	26-72	8	29	53.60	21	55.29	- 1.69
1457	43-60	3	28	16.36	20	15.53	.83

SUPPLEMENT I--(Continued)

Local well number	Grid block	Hydrogeologic unit	October 1980 Day	October 1980 Depth below land surface, in feet	April 1981 Day	April 1981 Depth below land surface, in feet	Change in water level, in feet, from October 1980 to April 1981
1458	34-59	8	30	41.73	21	45.17	- 3.44
1459	29-58	8	30	26.40	21	26.10	.30
1460	39-65	16	28	60.55	20	63.87	- 3.32
1461	28-67	8	30	49.75	21	41.74	8.01
1462	19-80	4	29	69.79	21	63.85	5.94
1463	13-80	18	29	4.46	21	3.00	1.46
1465	11-72	22	29	79.57	22	73.35	6.22
1466	15-87	18	29	78.40	21	70.99	7.41
1468	40-75	2	28	25.60	20	26.10	- .50
1469	21-74	1	29	45.58	21	44.19	1.39
1473	55-56	3	29	36.22	22	38.49	- 2.27
1476	54-45	3	29	19.50	21	19.00	.50
1482	28-16	17	30	17.80	23	15.88	1.92
1483	38-22	12	31	50.84	23	52.21	- 1.37
1485	32-10	6	31	29.71	23	33.40	- 3.69
1488	41-83	16	28	68.26	20	68.36	- .10
1489	9-39	13	30	38.69	21	33.95	4.74
1490	12-46	13	28	20.80	21	15.38	5.42
1491	47-49	3	29	54.81	21	55.05	- .24
1493	13-60	6	28	20.25	22	17.10	3.15
1495	18-68	4	30	26.48	22	25.43	1.05
1496	6-66	4	30	59.48	22	56.76	2.72
1497	15-29	13	29	32.96	20	30.01	2.95
1498	22-26	13	29	30.41	20	23.62	6.79
1500	29-45	16	29	28.33	20	25.52	2.81
1502	8-77	20	29	7.00	21	5.63	1.37
1503	64-60	3	29	26.11	21	29.16	- 3.05
1504	43-27	12	30	82.46	22	87.20	- 4.74
1505	34-16	2	31	91.20	23	95.31	- 4.11
1506	22-20	4	28	26.82	21	18.17	8.65
1507	29-7	6	31	13.62	23	13.29	.33
1622	18-92	21	28	47.38	21	40.72	6.66

ATTACHMENT A

Model program listing

The following is a listing of the model program used in this investigation. The modifications made by the authors to the original version (Trescott (1975) and Trescott and Larson (1976)) are indicated by asterisks in columns 75-77.

```
C     -------------------------------------------------------------------MAN0010
C     FINITE-DIFFERENCE MODEL FOR SIMULATION OF GROUND-WATER FLOW IN    MAN0020
C     THREE DIMENSIONS, SEPTEMBER, 1975 BY P.C. TRESCOTT, U. S. G. S.   MAN0030
C     WITH CONTRIBUTIONS TO MAIN, DATAI AND SOLVE BY S.P. LARSON        MAN0040
C     AND MODIFICATIONS BY J.M. GERHART AND G.J. LAZORCHICK, 1980-82      ***
C     -------------------------------------------------------------------MAN0050
C                                                                       MAN0060
C                                                                         ***
C     CHANGES TO ORIGINAL CODE MARKED WITH *** IN COLUMNS 75-77.          ***
C     PURPOSE OF CHANGE NOTED BY COMMENTS WHERE FEASIBLE.                 ***
C                                                                         ***
C     SPECIFICATIONS:                                                   MAN0070
      REAL *8YSTR                                                       MAN0080
C                                                                       MAN0090
      DIMENSION Y(400000),L(25),HEADNG(33),NAME(42),INFT(2,4),IOFT(9,5),  ***
     1DUM(3)                                                              ***
C                                                                       MAN0120
      EQUIVALENCE (YSTR,Y(1))                                           MAN0130
C                                                                       MAN0140
      COMMON /INTEGR/ I0,J0,K0,I1,J1,K1,I,J,K,NPER,KTH,ITMAX,LENGTH,KP,NMAN0150
     1WEL,NUMT,IFINAL,IT,KT,IHEAD,IDRAW,IFLO,IERR,I2,J2,K2,IMAX,ITMX1,NCMAN0160
     2H,IDK1,IDK2,IWATER,IQRE,IP,JP,IQ,JQ,IK,JK,K5,IPU1,IPU2,ITK,IEQN,KK  ***
     3K,KKKK,IR,ISTAT,MLTCHK,ISBOUT,IJKMAP,IVHMAP,IZTOZ,ITABLE,           ***
     4LAYDDN,ISLEAK,IOCTAP,IWLWD,IPPOUT                                   ***
      COMMON /SPARAM/ TMAX,CDLT,DELT,ERR,TEST,SUM,SUMP,QR               MAN0180
      COMMON /SARRAY/ ICHK(13),LEVEL1(9),LEVEL2(9)                      MAN0190
C                                                                       MAN0200
      DATA NAME/2*4H    ,4H    S,4HTART,4HING ,4HHEAD,4H    ,4H STO,4HRAGMAN0210
     1E,4H COE,4HFFIC,4HIENT,2*4H    ,4H  TR,4HANSM,4HISSI,4HVITY,5*4H  MAN0220
     2 ,4H  TK,4H   T,4HOPOG,4HRAPH,4HIC S,4HETTI,4HNG  ,2*4H    ,4HBOT   ***
     3T,4HOM E,4HLEVA,4HTION,2*4H    ,4H   R,4HECHA,4HRGE ,4HRATE/      MAN0240
      DATA INFT/4H(20F,4H4.0),4H(8F1,4H0.4),4H(8E1,4H0.3),4H(40F,4H2.0)/  ***
      DATA IOFT/4H(1H0,4H,I2,,4H2X,2,4H0F6.,4H1/(5,4HX,20,4HF6.1,4H)) ,MAN0260
     14H    ,4H(1H0,4H,I5,,4H14F9,4H.5/(,4H1H ,,4H5X,1,4H4F9.,4H5)) ,4H MAN0270
     2    ,4H(1H0,4H,I5,,4H10E1,4H2.5/,4H(1H ,4H,5X,,4H10E1,4H2.5),4H)  MAN0280
     3,4H(1H0,4H,I5,,4H10E1,4H1.3/,4H(1H ,4H,5X,,4H10E1,4H1.3),4H)   ,4H  ***
     4(1H0,4H,I2,,4H2X,5,4H0F2.,4H0/(5,4HX,50,4HF2.0,4H)) ,4H    /        ***
C                                                                       MAN0300
      DEFINE FILE 2(8,1520,U,KKK)                                       MAN0310
C     ...................................................................MAN0320
      KKK=0                                                               ***
      KKKK=0                                                              ***
C                                                                       MAN0330
C     ---READ TITLE, PROGRAM SIZE AND OPTIONS---                        MAN0340
      READ (5,200) HEADNG                                               MAN0350
      WRITE (6,190) HEADNG                                              MAN0360
      READ(5,160) I0,J0,K0,ITMAX,NCH,NZNS,IR,ISTAT,MLTCHK                 ***
      READ(5,165) ISBOUT,IJKMAP,IVHMAP,IZTOZ,ITABLE,LAYDDN,ISLEAK,        ***
     1IOCTAP,IWLWD,IPPOUT                                                 ***
      WRITE(6,180)     I0,J0,K0,ITMAX,NCH,NZNS,IR,ISTAT,MLTCHK,ISBOUT,IJK ***
     1MAP,IVHMAP,IZTOZ,ITABLE,LAYDDN,ISLEAK,IOCTAP,IWLWD,IPPOUT           ***
      READ (5,210) IDRAW,IHEAD,IFLO,IDK1,IDK2,IWATER,IQRE,IPU1,IPU2,ITK MAN0390
```

```
     1,IEQN                                                             MAN0395
      WRITE (6,220) IDRAW,IHEAD,IFLO,IDK1,IDK2,IWATER,IQRE,IPU1,IPU2,ITKMAN0400
     1,IEQN                                                             MAN0405
      IERR=0                                                            MAN0410
C                                                                       MAN0420
C     ---COMPUTE DIMENSIONS FOR ARRAYS---                               MAN0430
      J1=J0-1                                                           MAN0440
      I1=I0-1                                                           MAN0450
      K1=K0-1                                                           MAN0460
      I2=I0-2                                                           MAN0470
      J2=J0-2                                                           MAN0480
      K2=K0-2                                                           MAN0490
      IMAX=MAX0(I0,J0)                                                  MAN0500
      NCD=MAX0(1,NCH)                                                   MAN0510
      ITMX1=ITMAX+1                                                     MAN0520
      ISIZ=I0*J0*K0                                                     MAN0530
      IK1=I0*J0                                                         MAN0540
      IK2=MAX0(IK1*K1,1)                                                MAN0550
      ISUM=2*ISIZ+1                                                     MAN0560
      L(1)=1                                                            MAN0570
      DO 30 I=2,14                                                      MAN0580
      IF (I.NE.8) GO TO 20                                              MAN0590
      L(8)=ISUM                                                         MAN0600
      ISUM=ISUM+IK2                                                     MAN0610
      IF (IK2.EQ.1) GO TO 10                                            MAN0620
      IK=I0                                                             MAN0630
      JK=J0                                                             MAN0640
      K5=K1                                                             MAN0650
      GO TO 30                                                          MAN0660
   10 IK=1                                                              MAN0670
      JK=1                                                              MAN0680
      K5=1                                                              MAN0690
      GO TO 30                                                          MAN0700
   20 L(I)=ISUM                                                         MAN0710
      ISUM=ISUM+ISIZ                                                    MAN0720
   30 CONTINUE                                                          MAN0730
      L(15)=ISUM                                                        MAN0740
      ISUM=ISUM+J0                                                      MAN0750
      L(16)=ISUM                                                        MAN0760
      ISUM=ISUM+I0                                                      MAN0770
      L(17)=ISUM                                                        MAN0780
      ISUM=ISUM+K0                                                      MAN0790
      L(18)=ISUM                                                        MAN0800
      ISUM=ISUM+IMAX                                                    MAN0810
      L(19)=ISUM                                                        MAN0820
      ISUM=ISUM+K0*3                                                    MAN0830
      L(20)=ISUM                                                        MAN0840
      ISUM=ISUM+ITMX1                                                   MAN0850
      L(21)=ISUM                                                        MAN0860
      ISUM=ISUM+3*NCD                                                   MAN0870
      L(22)=ISUM                                                        MAN0880
      ISUM=ISUM+NCD                                                     MAN0890
      L(23)=ISUM                                                        MAN0900
```

```
      IF (IWATER.NE.ICHK(6)) GO TO 40                                   MAN0910
      ISUM=ISUM+IK1                                                     MAN0920
      L(24)=ISUM                                                        MAN0930
      ISUM=ISUM+IK1                                                     MAN0940
      IP=I0                                                             MAN0950
      JP=J0                                                             MAN0960
      GO TO 50                                                          MAN0970
   40 ISUM=ISUM+1                                                       MAN0980
      L(24)=ISUM                                                        MAN0990
      ISUM=ISUM+1                                                       MAN1000
      IP=1                                                              MAN1010
      JP=1                                                              MAN1020
   50 L(25)=ISUM                                                        MAN1030
      IF (IQRE.NE.ICHK(7)) GO TO 60                                     MAN1040
      ISUM=ISUM+IK1                                                     MAN1050
      IQ=I0                                                             MAN1060
      JQ=J0                                                             MAN1070
      GO TO 70                                                          MAN1080
   60 ISUM=ISUM+1                                                       MAN1090
      IQ=1                                                              MAN1100
      JQ=1                                                              MAN1110
C                                                                         ***
C     INCREASE SIZE FOR INPUT OF MODEL PARAMETERS BY HYDROGEOLOGIC UNIT.  ***
C                                                                         ***
   70 LZNS=ISUM                                                           ***
      ISUM=ISUM+IK1                                                       ***
      LKXU=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
      LKXL=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
      LKYU=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
      LKYL=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
      LKZU=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
      LKZL=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
      LBZU=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
      LBZL=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
      LSZU=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
      LSZL=ISUM                                                           ***
      ISUM=ISUM+NZNS                                                      ***
C                                                                         ***
C     INCREASE SIZE FOR HEAD DEPENDENT STREAM OPTION.                     ***
C                                                                         ***
      LRCG=ISUM                                                           ***
      ISUM=ISUM+ISIZ                                                      ***
      LRCL=ISUM                                                           ***
      ISUM=ISUM+ISIZ                                                      ***
```

```
      LRHSS=ISUM                                                          ***
      ISUM=ISUM+ISIZ                                                      ***
      LHB=ISUM                                                            ***
      ISUM=ISUM+ISIZ                                                      ***
C                                                                         ***
C     INCREASE SIZE FOR TOPOGRAPHIC MODIFICATION OF                       ***
C     HYDRAULIC CONDUCTIVITY.                                             ***
C                                                                         ***
      LPMULT=ISUM                                                         ***
      ISUM=ISUM+NZNS*5                                                    ***
      WRITE(6,170) ISUM                                                   ***
C                                                                       MAN1130
C     ---PASS INITIAL ADDRESSES OF ARRAYS TO SUBROUTINES---             MAN1140
      CALL DATAI(Y(L(1)),Y(L(2)),Y(L(3)),Y(L(4)),Y(L(5)),Y(L(6)),Y(L(7))MAN1150
     1,Y(L(8)),Y(L(9)),Y(L(15)),Y(L(16)),Y(L(17)),Y(L(19)),Y(L(23)),Y(L(MAN1160
     224)),Y(L(25)))                                                    MAN1170
      CALL STEP(Y(L(1)),Y(L(2)),Y(L(3)),Y(L(4)),Y(L(5)),Y(L(6)),Y(L(7)),MAN1180
     1Y(L(8)),Y(L(9)),Y(L(15)),Y(L(16)),Y(L(17)),Y(L(19)),Y(L(18)),Y(L(2MAN1190
     20)))                                                              MAN1200
      CALL SOLVE(Y(L(1)),Y(L(2)),Y(L(3)),Y(L(4)),Y(L(5)),Y(L(6)),Y(L(7))MAN1210
     1,Y(L(8)),Y(L(9)),Y(L(15)),Y(L(16)),Y(L(17)),Y(L(19)),Y(L(10)),Y(L(MAN1220
     211)),Y(L(12)),Y(L(13)),Y(L(14)),Y(L(20)),Y(L(25)),Y(LRCG),Y(LRCL),  ***
     3Y(LRHSS),Y(LHB))                                                    ***
      CALL COEF(Y(L(1)),Y(L(2)),Y(L(3)),Y(L(4)),Y(L(5)),Y(L(6)),Y(L(7)),MAN1240
     1Y(L(8)),Y(L(9)),Y(L(15)),Y(L(16)),Y(L(17)),Y(L(19)),Y(L(23)),Y(L(2MAN1250
     24)),Y(L(25)),Y(LZNS),Y(LKXU),Y(LKYU),Y(LKZU),Y(LBZU),               ***
     3 Y(LSZU),Y(LKXL),Y(LKYL),Y(LKZL),Y(LBZL),Y(LSZL),Y(LPMULT),         ***
     4NZNS)                                                               ***
      CALL CHECKI(Y(L(1)),Y(L(2)),Y(L(3)),Y(L(4)),Y(L(5)),Y(L(6)),Y(L(7)MAN1270
     1),Y(L(8)),Y(L(9)),Y(L(15)),Y(L(16)),Y(L(17)),Y(L(19)),Y(L(21)),Y(LMAN1280
     2(22)),Y(L(25)),Y(LRCG),Y(LRCL),Y(LRHSS),Y(LHB),                     ***
     3Y(LZNS),NZNS)                                                       ***
      CALL PRNTAI(Y(L(1)),Y(L(2)),Y(L(4)),Y(L(5)),Y(L(9)),Y(L(15)),Y(L(1MAN1300
     16)))                                                              MAN1310
C                                                                       MAN1320
C     ---START COMPUTATIONS---                                          MAN1330
C     ************************                                          MAN1340
C     ---READ AND WRITE DATA FOR GROUPS II AND III---                   MAN1350
      CALL DATAIN                                                       MAN1360
      IRN=1                                                             MAN1370
      NIJ=I0*J0                                                         MAN1380
      DO 80 K=1,K0                                                      MAN1390
      LOC=L(2)+(K-1)*NIJ                                                MAN1400
   80 CALL ARRAY(Y(LOC),INFT(1,2),IOFT(1,1),NAME(1),IRN,DUM)            MAN1410
      DO 90 K=1,K0                                                      MAN1420
      LOC=L(5)+(K-1)*NIJ                                                MAN1430
   90 CALL ARRAY(Y(LOC),INFT(1,1),IOFT(1,2),NAME(7),IRN,DUM)            MAN1440
      K=K0                                                              MAN1595
  120 IF (IWATER.NE.ICHK(6)) GO TO 130                                  MAN1590
      CALL ARRAY(Y(L(23)),INFT(1,4),IOFT(1,5),NAME(25),IRN,DUM)           ***
      CALL ARRAY(Y(L(24)),INFT(1,1),IOFT(1,1),NAME(31),IRN,DUM)         MAN1610
  130 IF(IQRE.EQ.ICHK(7)) CALL ARRAY(Y(L(25)),INFT(1,2),IOFT(1,4),NAME(3MAN1620
     17),IRN,DUM)                                                       MAN1630
```

```
C                                                                        ***
C     HEAD DEPENDENT STREAM OPTION ADDITIONS.                            ***
C                                                                        ***
      DO 134 K=1,KO                                                      ***
      LOC=LRCG+(K-1)*NIJ                                                 ***
  134 CALL ARRAY(Y(LOC),INFT(1,3),IOFT(1,4),24H  R  GAINING COEFFICIENT, ***
     1IRN,DUM)                                                           ***
      DO 135 K=1,KO                                                      ***
      LOC=LRCL+(K-1)*NIJ                                                 ***
  135 CALL ARRAY(Y(LOC),INFT(1,3),IOFT(1,4),24H  R   LOSING COEFFICIENT, ***
     1IRN,DUM)                                                           ***
      DO 136 K=1,KO                                                      ***
      LOC=LRHSS+(K-1)*NIJ                                                ***
  136 CALL ARRAY(Y(LOC),INFT(1,1),IOFT(1,1),24H            FIXED R HEAD, ***
     1IRN,DUM)                                                           ***
      DO 137 K=1,KO                                                      ***
      LOC=LHB+(K-1)*NIJ                                                  ***
  137 CALL ARRAY(Y(LOC),INFT(1,1),IOFT(1,1),24H  R  LEAKAGE CUTOFF HEAD, ***
     1IRN,DUM)                                                           ***
C                                                                        ***
C     INPUT OF MODEL PARAMETERS BY HYDROGEOLOGIC UNIT.                   ***
C                                                                        ***
      CALL INPUT                                                         ***
      CALL MDAT
C
C     ---COMPUTE TRANSMISSIVITY FOR UNCONFINED LAYER---
      IF (IWATER.EQ.ICHK(6)) CALL TRANS(1)
C
C     ---COMPUTE T COEFFICIENTS---
      CALL TCOF
C
C     ---COMPUTE ITERATION PARAMETERS---
      CALL ITER
C
C     ---READ TIME PARAMETERS AND PUMPING DATA FOR A NEW PUMPING PERIOD-
  140 CALL NEWPER
C
      KT=0
      IFINAL=0
C
C     ---START NEW TIME STEP COMPUTATIONS---
  150 CALL NEWSTP
C
C     ---START NEW ITERATION IF MAXIMUM NO. ITERATIONS NOT EXCEEDED---
      CALL NEWITA
C
C     ---PRINT OUTPUT AT DESIGNATED TIME STEPS---
      CALL OUTPUT
C
C     ---LAST TIME STEP IN PUMPING PERIOD ?---
      IF (IFINAL.NE.1) GO TO 150
C
C     ---CHECK FOR NEW PUMPING PERIOD---
```

```
      IF (KP.LT.NPER) GO TO 140                                         MAN1940
C                                                                       MAN1950
      STOP                                                              MAN1960
C                                                                       MAN1970
C     ---FORMATS---                                                     MAN1980
C                                                                       MAN1990
C                                                                       MAN2000
C                                                                       MAN2010
  160 FORMAT(6I10,3I5)                                                    ***
  165 FORMAT(10I5)                                                        ***
  170 FORMAT ('0',54X,'WORDS OF VECTOR Y USED =',I7)                    MAN2030
  180 FORMAT ('0',62X,'NUMBER OF ROWS =',I5/60X,'NUMBER OF COLUMNS =',I5MAN2040
     1/61X,'NUMBER OF LAYERS =',I5//39X,'MAXIMUM PERMITTED NUMBER OF ITEMAN2050
     2RATIONS =',I5//48X,'NUMBER OF CONSTANT HEAD NODES =',I5,            ***
     3 //,54X,'NUMBER OF AQUIFER ZONES =',I5//76X,'IR =',                 ***
     4I1,//76X,'ISTAT =',I1//76X,'MLTCHK=',I1//76X,'ISBOUT=',I1//76X,'IJ  ***
     5KMAP=',I1//76X,'IVHMAP=',I1//76X,'IZTOZ=',I1//76X,'ITABLE=',I1//76  ***
     6X,'LAYDDN=',I1//76X,'ISLEAK=',I1,//,76X,'IOCTAP=',I1//76X,          ***
     7'IWLWD=',I1//76X,'IPPOUT=',I1)                                      ***
  190 FORMAT ('1',33A4)                                                 MAN2070
  200 FORMAT (20A4)                                                     MAN2080
  210 FORMAT (16(A4,1X))                                                MAN2090
  220 FORMAT ('-SIMULATION OPTIONS:  ',11(A4,4X))                       MAN2100
  230 FORMAT (1H0,44X,'DIRECTIONAL TRANSMISSIVITY MULTIPLICATION FACTORSMAN2110
     1 FOR LAYER',I3,/,76X,'X =',G15.7/76X,'Y =',G15.7/76X,'Z =',G15.7) MAN2120
      END                                                               MAN2130


      SUBROUTINE DATAI(PHI,STRT,OLD,T,S,TR,TC,TK,WELL,DELX,DELY,DELZ,FACDAT0010
     1T,PERM,BOTTOM,QRE)                                                DAT0020
C     ------------------------------------------------------------------DAT0030
C     READ AND WRITE DATA                                               DAT0040
C     ------------------------------------------------------------------DAT0050
C                                                                       DAT0060
C     SPECIFICATIONS:                                                   DAT0070
      REAL *8PHI                                                        DAT0080
      REAL *8XLABEL,YLABEL,TITLE,XN1,MESUR                              DAT0090
C                                                                       DAT0100
      DIMENSION NAME(42)                                                  ***
      DIMENSION PHI(I0,J0,K0), STRT(I0,J0,K0), OLD(I0,J0,K0), T(I0,J0,K0DAT0110
     1), S(I0,J0,K0), TR(I0,J0,K0), TC(I0,J0,K0), TK(IK,JK,K5), WELL(I0,DAT0120
     2J0,K0), DELX(J0), DELY(I0), DELZ(K0), FACT(K0,3), PERM(IP,JP), BOTDAT0130
     3TOM(IP,JP), QRE(IQ,JQ), TF(3), A(I0,J0), IN(6), IOFT(9), INFT(2)  DAT0140
C                                                                       DAT0150
      COMMON /INTEGR/ I0,J0,K0,I1,J1,K1,I,J,K,NPER,KTH,ITMAX,LENGTH,KP,NDAT0160
     1WEL,NUMT,IFINAL,IT,KT,IHEAD,IDRAW,IFLO,IERR,I2,J2,K2,IMAX,ITMX1,NCDAT0170
     2H,IDK1,IDK2,IWATER,IQRE,IP,JP,IQ,JQ,IK,JK,K5,IPU1,IPU2,ITK,IEQN,KK  ***
     3K,KKKK,IR,ISTAT,MLTCHK,ISBOUT,IJKMAP,IVHMAP,IZTOZ,ITABLE,           ***
     4LAYDDN,ISLEAK,IOCTAP,IWLWD,IPPOUT                                   ***
      COMMON /SPARAM/ TMAX,CDLT,DELT,ERR,TEST,SUM,SUMP,QR               DAT0190
      COMMON /SARRAY/ ICHK(13),LEVEL1(9),LEVEL2(9)                      DAT0200
      COMMON /CK/ ETFLXT,STORT,QRET,CHST,CHDT,FLUXT,PUMPT,CFLUXT,FLXNT  DAT0210
      COMMON /PR/ XLABEL(3),YLABEL(6),TITLE(6),XN1,MESUR,PRNT(122),BLANKDAT0220
```

```
     1(60),DIGIT(122),VF1(6),VF2(6),VF3(7),XSCALE,DINCH,SYM(17),XN(100),
     2YN(13),NA(4),N1,N2,N3,YSCALE,FACT1,FACT2
      DATA NAME/2*4H    ,4H   S,4HTART,4HING ,4HHEAD,4H    ,4H STO,4HRAG  ***
     1E,4H COE,4HFFIC,4HIENT,2*4H    ,4H  TR,4HANSM,4HISSI,4HVITY,5*4H    ***
     2 ,4H  TK,4H   T,4HOPOG,4HRAPH,4HIC S,4HETTI,4HNG  ,2*4H    ,4HBOT   ***
     3T,4HOM E,4HLEVA,4HTION,2*4H    ,4H   R,4HECHA,4HRGE ,4HRATE/        ***
      RETURN
C     ..................................................................
C     *******************
      ENTRY DATAIN
C     *******************
C
C     ---READ AND WRITE SCALAR PARAMETERS---
      READ (5,330) NPER,KTH,ERR,LENGTH
      WRITE (6,340) NPER,KTH,ERR
      READ (5,460) XSCALE,YSCALE,DINCH,FACT1,(LEVEL1(I),I=1,9),FACT2,(LE
     1VEL2(I),I=1,9),MESUR
      IF (XSCALE.NE.0.) WRITE (6,470) XSCALE,YSCALE,MESUR,MESUR,DINCH,FA
     1CT1,LEVEL1,FACT2,LEVEL2
C
C     ---READ CUMULATIVE MASS BALANCE PARAMETERS---
      READ (5,450) SUM,SUMP,PUMPT,CFLUXT,QRET,CHST,CHDT,FLUXT,STORT,ETFL
     1XT,FLXNT
      IF (IDK1.EQ.ICHK(4)) GO TO 20
      IF (IPU1.NE.ICHK(8)) GO TO 50
C
C     ---READ INITIAL HEAD VALUES FROM CARDS---
      DO 10 K=1,KO
      DO 10 I=1,IO
   10 READ (5,360) (PHI(I,J,K),J=1,JO)
      GO TO 30
C
C     ---READ INITIAL HEAD AND MASS BALANCE PARAMETERS FROM DISK---
   20 READ (4) PHI,SUM,SUMP,PUMPT,CFLUXT,QRET,CHST,CHDT,FLUXT,STORT,ETFL
     1XT,FLXNT
      REWIND 4
   30 WRITE (6,430) SUM
      DO 40 K=1,KO
      WRITE (6,440) K
      DO 40 I=1,IO
   40 WRITE (6,350) I,(PHI(I,J,K),J=1,JO)
C
   50 DO 60 K=1,KO
      DO 60 I=1,IO
      DO 60 J=1,JO
      WELL(I,J,K)=0.
      TR(I,J,K)=0.
      TC(I,J,K)=0.
      IF (K.NE.KO) TK(I,J,K)=0.
   60 CONTINUE
      RETURN
C     ********************
      ENTRY ARRAY(A,INFT,IOFT,IN,IRN,TF)
```

```
C     ********************
      READ (5,330) FAC,IVAR,IPRN,TF,IRECS,IRECD
      IC=4*IRECS+2*IVAR+IPRN+1
      GO TO (70,70,90,90,120,120), IC
   70 DO 80 I=1,IO
      DO 80 J=1,JO
   80 A(I,J)=FAC
      IF(IN(2).EQ.NAME(8).OR.IN(1).EQ.NAME(25)) GO TO 140
      WRITE (6,280) IN,FAC,K
      GO TO 140
   90 IF (IC.EQ.3) WRITE (6,290) IN,K
      DO 110 I=1,IO
      READ (5,INFT) (A(I,J),J=1,JO)
      DO 100 J=1,JO
  100 A(I,J)=A(I,J)*FAC
  110 IF (IC.EQ.3) WRITE (6,IOFT) I,(A(I,J),J=1,JO)
      GO TO 140
  120 READ (2'IRN) A
      IF (IC.EQ.6) GO TO 140
      WRITE (6,290) IN,K
      DO 130 I=1,IO
  130 WRITE (6,IOFT) I,(A(I,J),J=1,JO)
  140 IF (IRECD.EQ.1) WRITE (2'IRN) A
      IRN=IRN+1
      RETURN
C     ********************
      ENTRY MDAT
C     ********************
      DO 150 K=1,KO
      DO 150 I=1,IO
      DO 150 J=1,JO
      IF (I.EQ.1.OR.I.EQ.IO.OR.J.EQ.1.OR.J.EQ.JO) T(I,J,K)=0.
      IF (IDK1.NE.ICHK(4).AND.IPU1.NE.ICHK(8)) PHI(I,J,K)=STRT(I,J,K)
      IF (K.NE.KO.OR.IWATER.NE.ICHK(6)) GO TO 150
      IF (I.EQ.1.OR.I.EQ.IO.OR.J.EQ.1.OR.J.EQ.JO) PERM(I,J)=0.
  150 CONTINUE
C     ............................ DELX ............................
      READ (5,330) FAC,IVAR,IPRN
      IF (IVAR.EQ.1) READ (5,330) (DELX(J),J=1,JO)
      DO 170 J=1,JO
      IF (IVAR.NE.1) GO TO 160
      DELX(J)=DELX(J)*FAC
      GO TO 170
  160 DELX(J)=FAC
  170 CONTINUE
      IF (IVAR.EQ.1.AND.IPRN.NE.1) WRITE (6,370) (DELX(J),J=1,JO)
      IF (IVAR.EQ.0) WRITE (6,300) FAC
C     ............................ DELY ............................
      READ (5,330) FAC,IVAR,IPRN
      IF (IVAR.EQ.1) READ (5,330) (DELY(I),I=1,IO)
      DO 190 I=1,IO
      IF (IVAR.NE.1) GO TO 180
      DELY(I)=DELY(I)*FAC
```

```
      GO TO 190
  180 DELY(I)=FAC
  190 CONTINUE
      IF (IVAR.EQ.1.AND.IPRN.NE.1) WRITE (6,380) (DELY(I),I=1,IO)
      IF (IVAR.EQ.0) WRITE (6,310) FAC
C     ............................. DELZ ..............................
      READ (5,330) FAC,IVAR,IPRN
      IF (IVAR.EQ.1) READ (5,330) (DELZ(K),K=1,KO)
      DO 210 K=1,KO
      IF (IVAR.NE.1) GO TO 200
      DELZ(K)=DELZ(K)*FAC
      GO TO 210
  200 DELZ(K)=FAC
  210 CONTINUE
      IF (IVAR.EQ.1.AND.IPRN.NE.1) WRITE (6,390) (DELZ(K),K=1,KO)
      IF (IVAR.EQ.0) WRITE (6,320) FAC
C
C     ---INITIALIZE VARIABLES---
      B=0.
      D=0.
      F=0.
      H=0.
      SU=0.
      Z=0.
      IF (XSCALE.NE.0.) CALL MAP
      RETURN
C     ..................................................................
C     ---READ TIME PARAMETERS AND PUMPING DATA FOR A NEW PUMPING PERIOD-
C     *********************
      ENTRY NEWPER
C     *********************
C
      READ (5,330) KP,KPM1,NWEL,TMAX,NUMT,CDLT,DELT
C
C     ---COMPUTE ACTUAL DELT AND NUMT---
      TM=0.0
      DO 220 I=1,NUMT
      DT=CDLT*DT
      TM=TM+DT
      IF (TM.GE.TMAX) GO TO 230
  220 CONTINUE
      GO TO 240
  230 DELT=TMAX/TM*DELT
      NUMT=I
  240 WRITE (6,400) KP,TMAX,NUMT,DELT,CDLT
      DELT=DELT*3600.
      TMAX=TMAX*86400.
      SUMP=0.0
C
C     ---READ AND WRITE WELL PUMPING RATES---
      IF(KP.GT.1) GO TO 265
      WRITE (6,410) NWEL
      IF (NWEL.EQ.0) GO TO 265
```

```
      DO 245 K=1,KO                                                     DAT1761
      DO 245 I=1,IO                                                     DAT1762
      DO 245 J=1,JO                                                     DAT1763
  245 WELL(I,J,K)=0.0                                                   DAT1764
      DO 250 II=1,NWEL                                                  DAT1770
      READ (5,330) K,I,J,WELL(I,J,K)                                    DAT1780
      WRITE (6,420) K,I,J,WELL(I,J,K)                                   DAT1790
  250 WELL(I,J,K)=WELL(I,J,K)/(DELX(J)*DELY(I))                         DAT1800
C                                                                         ***
C     OPTION TO READ IN NEW RECHARGE RATE FOR EACH PUMPING PERIOD.        ***
C                                                                         ***
  265 IF(KP.EQ.1)  RETURN                                                 ***
      PARAM=0.                                                            ***
      DO 270 I=1,IO                                                       ***
      DO 270 J=1,JO                                                       ***
  270 QRE(I,J)=0.                                                         ***
      READ(5,276) PARAM                                                   ***
      DO 272 I=1,IO                                                       ***
  272 READ(5,278) (QRE(I,J),J=1,JO)                                       ***
      DO 274 I=1,IO                                                       ***
      DO 274 J=1,JO                                                       ***
  274 QRE(I,J)=QRE(I,J)*PARAM                                             ***
      RETURN                                                              ***
C                                                                       DAT1820
C     ---FORMATS---                                                     DAT1830
C                                                                       DAT1840
C                                                                       DAT1850
C                                                                       DAT1860
  276 FORMAT(E10.3)                                                       ***
  278 FORMAT(8F10.4)                                                      ***
  280 FORMAT (1H0,52X,6A4,' =',G15.7,' FOR LAYER',I3)                   DAT1870
  290 FORMAT (1H1,45X,6A4,' MATRIX, LAYER',I3/46X,41('-'))              DAT1880
  300 FORMAT('1',72X,'DELX =',G15.7)                                      ***
  310 FORMAT ('0',72X,'DELY =',G15.7)                                   DAT1900
  320 FORMAT ('0',72X,'DELZ =',G15.7)                                   DAT1910
  330 FORMAT (8G10.0)                                                   DAT1920
  340 FORMAT ('0',51X,'NUMBER OF PUMPING PERIODS =',I5/49X,'TIME STEPS BDAT1930
     1ETWEEN PRINTOUTS =',I5//51X,'ERROR CRITERIA FOR CLOSURE =',G15.7/)DAT1940
  350 FORMAT ('0',I2,2X,20F6.1/(5X,20F6.1))                             DAT1950
  360 FORMAT (8F10.4)                                                   DAT1960
  370 FORMAT (1H1,46X,40HGRID SPACING IN PROTOTYPE IN X DIRECTION/47X,40DAT1970
     1('-')//('0',12F10.0))                                             DAT1980
  380 FORMAT (1H-,46X,40HGRID SPACING IN PROTOTYPE IN Y DIRECTION/47X,40DAT1990
     1('-')//('0',12F10.0))                                             DAT2000
  390 FORMAT (1H-,46X,40HGRID SPACING IN PROTOTYPE IN Z DIRECTION/47X,40DAT2010
     1('-')//('0',12F10.0))                                             DAT2020
  400 FORMAT ('-',50X,'PUMPING PERIOD NO.',I4,':',F10.2,' DAYS'/51X,38('DAT2030
     1-')//53X,'NUMBER OF TIME STEPS=',I6//59X,'DELT IN HOURS =',F10.3//DAT2040
     253X,'MULTIPLIER FOR DELT =',F10.3)                                DAT2050
  410 FORMAT ('-',63X,I4,' WELLS'/65X,9('-')//50X,'K',9X,'I',9X,'J     PUDAT2060
     1MPING RATE'/)                                                     DAT2070
  420 FORMAT (41X,3I10,2F13.2)                                          DAT2080
  430 FORMAT ('-',40X,' CONTINUATION - HEAD AFTER ',G20.7,' SEC PUMPING DAT2090
```

```
     1'/42X,58('-'))
  440 FORMAT ('1',55X,'INITIAL  HEAD MATRIX, LAYER',I3/56X,30('-'))
  450 FORMAT (4G20.10)
  460 FORMAT (3G10.0,2(G10.0,9I1,1X),A8)
  470 FORMAT ('0',30X,'ON ALPHAMERIC MAP:'/40X,'MULTIPLICATION FACTOR FO
     1R X DIMENSION =',G15.7/40X,'MULTIPLICATION FACTOR FOR Y DIMENSION
     2=',G15.7/55X,'MAP SCALE IN UNITS OF  ',A11/50X,'NUMBER OF ',A8,' P
     3ER INCH =',G15.7/43X,'MULTIPLICATION FACTOR FOR DRAWDOWN =',G15.7,
     4' PRINTED FOR LAYERS',9I2/47X,'MULTIPLICATION FACTOR FOR HEAD =',G
     515.7,' PRINTED FOR LAYERS',9I2)
      END


      SUBROUTINE STEP(PHI,STRT,OLD,T,S,TR,TC,TK,WELL,DELX,DELY,DELZ,FACT
     1,DDN,TEST3)
C     ------------------------------------------------------------------
C     INITIALIZE DATA FOR A NEW TIME STEP AND PRINT RESULTS
C     ------------------------------------------------------------------
C
C     SPECIFICATIONS:
      REAL *8PHI
      REAL *8XLABEL,YLABEL,TITLE,XN1,MESUR
C
      DIMENSION PHI(I0,J0,K0), STRT(I0,J0,K0), OLD(I0,J0,K0), T(I0,J0,K0
     1), S(I0,J0,K0), TR(I0,J0,K0), TC(I0,J0,K0), TK(IK,JK,K5), WELL(I0,
     2J0,K0), DELX(J0), DELY(I0), DELZ(K0), FACT(K0,3), DDN(IMAX), TEST3
     3(ITMX1), ITTO(50)
      DIMENSION IIDDN(68,100,2)                                          ***
C
      COMMON /INTEGR/ I0,J0,K0,I1,J1,K1,I,J,K,NPER,KTH,ITMAX,LENGTH,KP,N
     1WEL,NUMT,IFINAL,IT,KT,IHEAD,IDRAW,IFLO,IERR,I2,J2,K2,IMAX,ITMX1,NC
     2H,IDK1,IDK2,IWATER,IQRE,IP,JP,IQ,JQ,IK,JK,K5,IPU1,IPU2,ITK,IEQN,KK ***
     3K,KKKK,IR,ISTAT,MLTCHK,ISBOUT,IJKMAP,IVHMAP,IZTOZ,ITABLE,          ***
     4LAYDDN,ISLEAK,IOCTAP,IWLWD,IPPOUT                                  ***
      COMMON /SPARAM/ TMAX,CDLT,DELT,ERR,TEST,SUM,SUMP,QR
      COMMON /SARRAY/ ICHK(13),LEVEL1(9),LEVEL2(9)
      COMMON /CK/ ETFLXT,STORT,QRET,CHST,CHDT,FLUXT,PUMPT,CFLUXT,FLXNT
      COMMON /PR/ XLABEL(3),YLABEL(6),TITLE(6),XN1,MESUR,PRNT(122),BLANK
     1(60),DIGIT(122),VF1(6),VF2(6),VF3(7),XSCALE,DINCH,SYM(17),XN(100),
     2YN(13),NA(4),N1,N2,N3,YSCALE,FACT1,FACT2
      RETURN
C     ..................................................................
C     ********************
      ENTRY NEWSTP
C     ********************
      KT=KT+1
      IT=0
      DO 10 K=1,K0
      DO 10 I=1,I0
      DO 10 J=1,J0
   10 OLD(I,J,K)=PHI(I,J,K)
      DELT=CDLT*DELT
      SUM=SUM+DELT
```

```
      SUMP=SUMP+DELT
      DAYSP=SUMP/86400.
      YRSP=DAYSP/365.
      HRS=SUM/3600.
      SMIN=HRS*60.
      DAYS=HRS/24.
      YRS=DAYS/365.
      RETURN
C
C     ---PRINT OUTPUT AT DESIGNATED TIME STEPS---
C     ********************
      ENTRY OUTPUT
C     ********************
C
C     OPTION FOR MAPS OF DRAWDOWN AND VERTICAL
C     HEAD DIFFERENCE BETWEEN LAYERS.
C
      DO 15 K=1,KO
      DO 15 I=1,IO
      DO 15 J=1,JO
   15 IIDDN(I,J,K)=0
      IF (KT.EQ.NUMT) IFINAL=1
      ITTO(KT)=IT
      IF (IT.LE.ITMAX) GO TO 20
      IT=IT-1
      ITTO(KT)=IT
      IERR=2
C
C     ---IF MAXIMUM ITERATIONS EXCEEDED,WRITE RESULTS ON DISK OR CARDS--
      IF (IDK2.EQ.ICHK(5)) WRITE (4) PHI,SUM,SUMP,PUMPT,CFLUXT,QRET,CHST
     1,CHDT,FLUXT,STORT,ETFLXT,FLXNT
      IF (IPU2.EQ.ICHK(9)) WRITE (7,230) SUM,SUMP,PUMPT,CFLUXT,QRET,CHST
     1,CHDT,FLUXT,STORT,ETFLXT,FLXNT
C
   20 IF (IFLO.EQ.ICHK(3)) CALL CHECK
      IF (IERR.EQ.2) GO TO 30
      IF (MOD(KT,KTH).NE.0.AND.IFINAL.NE.1) RETURN
   30 WRITE (6,210) KT,DELT,SUM,SMIN,HRS,DAYS,YRS,DAYSP,YRSP
      IF (IFLO.EQ.ICHK(3)) CALL CWRITE
      IT=IT+1
      WRITE (6,180) (TEST3(J),J=1,IT)
      I3=1
      I5=0
  352 I5=I5+40
      I4=MIN0(KT,I5)
      WRITE (6,240) (I,I=I3,I4)
      WRITE (6,260)
      WRITE (6,250) (ITTO(I),I=I3,I4)
      WRITE (6,260)
      IF(KT.LE.I5) GO TO 353
      I3=I3+40
      GO TO 352
C
```

```
C     ---PRINT MAPS---
  353 IF (XSCALE.EQ.0.) GO TO 70
      IF (FACT1.EQ.0.) GO TO 50
      DO 40 IA=1,9
      II=LEVEL1(IA)
      IF (II.EQ.0) GO TO 50
   40 CALL PRNTA(1,II)
   50 IF (FACT2.EQ.0.) GO TO 70
      DO 60 IA=1,9
      II=LEVEL2(IA)
      IF (II.EQ.0) GO TO 70
   60 CALL PRNTA(2,II)
   70 IF (IDRAW.NE.ICHK(1)) GO TO 100
C
C     ---PRINT DRAWDOWN---
      DO 90 K=1,KO
      WRITE (6,200) K
      DO 90 I=1,IO
      DO 80 J=1,JO
   80 DDN(J)=STRT(I,J,K)-PHI(I,J,K)
   90 WRITE (6,170) I,(DDN(J),J=1,JO)
  100 IF (IHEAD.NE.ICHK(2)) GO TO 111                           ***
C
C     ---PRINT HEAD MATRIX---
      DO 110 K=1,KO
      WRITE (6,190) K
      DO 110 I=1,IO
  110 WRITE (6,170) I,(PHI(I,J,K),J=1,JO)
C                                                               ***
C     OPTION FOR MAPS OF DRAWDOWN AND VERTICAL                  ***
C     HEAD DIFFERENCE BETWEEN LAYERS.                           ***
C                                                               ***
  111 IF(IFINAL.NE.1) GO TO 120                                 ***
      IF(IJKMAP.NE.1) GO TO 108                                 ***
      MAPS=1                                                    ***
  109 DO 112 K=1,KO                                             ***
      DO 112 I=1,IO                                             ***
      DO 112 J=1,JO                                             ***
      IF(MAPS.EQ.1) WWW=STRT(I,J,K)-PHI(I,J,K)                  ***
      IF(MAPS.EQ.2) WWW=PHI(I,J,2)-PHI(I,J,1)                   ***
  112 IIDDN(I,J,K)=WWW                                          ***
      DO 126 L=1,2                                              ***
      IF(L.EQ.1.AND.MAPS.EQ.2) GO TO 126                        ***
      IF(MAPS.EQ.2) GO TO 107                                   ***
      WRITE(6,600) L                                            ***
      GO TO 106                                                 ***
  107 WRITE(6,650)                                              ***
  106 WRITE(6,1000)                                             ***
      DO 113 I=3,29                                             ***
  113 WRITE(6,900) I,(IIDDN(I,J,L),J=3,26)                      ***
      WRITE(6,1100)                                             ***
      DO 114 I=3,29                                             ***
  114 WRITE(6,900) I,(IIDDN(I,J,L),J=27,50)                     ***
```

```
      WRITE(6,1200)                                                      ***
      DO 115 I=3,29                                                      ***
  115 WRITE(6,900) I,(IIDDN(I,J,L),J=51,74)                              ***
      WRITE(6,1300)                                                      ***
      DO 116 I=3,29                                                      ***
  116 WRITE(6,800) (IIDDN(I,J,L),J=75,98),I                              ***
      WRITE(6,1000)                                                      ***
      DO 117 I=30,56                                                     ***
  117 WRITE(6,900) I,(IIDDN(I,J,L),J=3,26)                               ***
      WRITE(6,1100)                                                      ***
      DO 118 I=30,56                                                     ***
  118 WRITE(6,900) I,(IIDDN(I,J,L),J=27,50)                              ***
      WRITE(6,1200)                                                      ***
      DO 119 I=30,56                                                     ***
  119 WRITE(6,900) I,(IIDDN(I,J,L),J=51,74)                              ***
      WRITE(6,1300)                                                      ***
      DO 121 I=30,56                                                     ***
  121 WRITE(6,800) (IIDDN(I,J,L),J=75,98),I                              ***
      WRITE(6,700)                                                       ***
      DO 122 I=57,66                                                     ***
  122 WRITE(6,900) I,(IIDDN(I,J,L),J=3,26)                               ***
      WRITE(6,1400)                                                      ***
      WRITE(6,700)                                                       ***
      DO 123 I=57,66                                                     ***
  123 WRITE(6,900) I,(IIDDN(I,J,L),J=27,50)                              ***
      WRITE(6,1500)                                                      ***
      WRITE(6,700)                                                       ***
      DO 124 I=57,66                                                     ***
  124 WRITE(6,900) I,(IIDDN(I,J,L),J=51,74)                              ***
      WRITE(6,1600)                                                      ***
      WRITE(6,700)                                                       ***
      DO 125 I=57,66                                                     ***
  125 WRITE(6,800) (IIDDN(I,J,L),J=75,98),I                              ***
      WRITE(6,1700)                                                      ***
  126 CONTINUE                                                           ***
      IF(MAPS.EQ.2) GO TO 120                                            ***
  108 IF(IVHMAP.NE.1) GO TO 120                                          ***
      MAPS=2                                                             ***
      GO TO 109                                                          ***
C                                                                       STP1040
C     ---WRITE ON DISK---                                               STP1050
  120 IF (IERR.EQ.2) GO TO 130                                          STP1060
      IF (KP.LT.NPER.OR.IFINAL.NE.1) RETURN                             STP1070
      IF (IDK2.EQ.ICHK(5)) WRITE (4) PHI,SUM,SUMP,PUMPT,CFLUXT,QRET,CHSTSTP1080
     1,CHDT,FLUXT,STORT,ETFLXT,FLXNT                                    STP1090
C                                                                       STP1100
C     ---PUNCHED OUTPUT---                                              STP1110
  130 IF (IPU2.NE.ICHK(9)) GO TO 160                                    STP1120
      IF (IERR.EQ.2) GO TO 140                                          STP1130
      WRITE (7,230) SUM,SUMP,PUMPT,CFLUXT,QRET,CHST,CHDT,FLUXT,STORT,ETFSTP1140
     1LXT,FLXNT                                                         STP1150
  140 DO 150 K=1,KO                                                     STP1160
      DO 150 I=1,IO                                                     STP1165
```

```
  150 WRITE (7,220)  (PHI(I,J,K),J=1,J0)                                  STP1170
  160 IF (IERR.EQ.2) STOP                                                 STP1180
      RETURN                                                              STP1190
C                                                                         STP1200
C     ---FORMATS---                                                       STP1210
C                                                                         STP1220
C                                                                         STP1230
C                                                                         STP1240
  170 FORMAT ('0',I4,18F7.2/(5X,18F7.2))                                  STP1250
  180 FORMAT ('1MAXIMUM HEAD CHANGE FOR EACH ITERATION:'/' ',39('-')/('0STP1260
     1',10F12.4))                                                         STP1270
  190 FORMAT ('1',55X,'HEAD MATRIX, LAYER',I3/56X,21('-'))                STP1280
  200 FORMAT ('1',55X,'   DRAWDOWN, LAYER',I3/59X,18('-'))                STP1290
  210 FORMAT (1H1,44X,57('-')/45X,'| ',14X,'TIME STEP NUMBER =',I9,14X,'| STP1300
     1'/45X,57('-')//50X,29HSIZE OF TIME STEP IN SECONDS=,F14.2//55X,'TOSTP1310
     2TAL SIMULATION TIME IN SECONDS=',F14.2/80X,8HMINUTES=,F14.2/82X,6HSTP1320
     3HOURS=,F14.2/83X,5HDAYS=,F14.2/82X,'YEARS=',F14.2///45X,'DURATION STP1330
     4OF CURRENT PUMPING PERIOD IN DAYS=',F14.2/82X,'YEARS=',F14.2//)     STP1340
  220 FORMAT (10F8.4)                                                     STP1350
  230 FORMAT (4G20.10)                                                    STP1360
  240 FORMAT ('0TIME STEP :',40I3)                                        STP1370
  250 FORMAT ('0ITERATIONS:',40I3)                                        STP1380
  260 FORMAT (' ',10('-'))                                                STP1390
  600 FORMAT('1',10X,'LAYER  ',I1,'  DRAWDOWN MAP')                         ***
  650 FORMAT('1',10X,'MAP OF VERTICAL HEAD DIFFERENCE BETWEEN LAYERS')      ***
  700 FORMAT('1')                                                           ***
  800 FORMAT('0',24(1X,I4),2X,I2)                                           ***
  900 FORMAT('0',2X,I2,1X,24(1X,I4))                                        ***
 1000 FORMAT('1',9X,'3',4X,'4',4X,'5',4X,'6',4X,'7',4X,'8',4X,'9',3X,'10    ***
     1',3X,'11',3X,'12',3X,'13',3X,'14',3X,'15',3X,'16',3X,'17',3X,'18',    ***
     23X,'19',3X,'20',3X,'21',3X,'22',3X,'23',3X,'24',3X,'25',3X,'26')      ***
 1100 FORMAT('1',8X,'27',3X,'28',3X,'29',3X,'30',3X,'31',3X,'32',3X,'33'    ***
     1,3X,'34',3X,'35',3X,'36',3X,'37',3X,'38',3X,'39',3X,'40',3X,'41',3    ***
     2X,'42',3X,'43',3X,'44',3X,'45',3X,'46',3X,'47',3X,'48',3X,'49',3X,    ***
     3'50')                                                                 ***
 1200 FORMAT('1',8X,'51',3X,'52',3X,'53',3X,'54',3X,'55',3X,'56',3X,'57'    ***
     1,3X,'58',3X,'59',3X,'60',3X,'61',3X,'62',3X,'63',3X,'64',3X,'65',3    ***
     2X,'66',3X,'67',3X,'68',3X,'69',3X,'70',3X,'71',3X,'72',3X,'73',3X,    ***
     3'74')                                                                 ***
 1300 FORMAT('1',3X,'75',3X,'76',3X,'77',3X,'78',3X,'79',3X,'80',3X,'81'    ***
     1,3X,'82',3X,'83',3X,'84',3X,'85',3X,'86',3X,'87',3X,'88',3X,'89',3    ***
     2X,'90',3X,'91',3X,'92',3X,'93',3X,'94',3X,'95',3X,'96',3X,'97',       ***
     33X,'98')                                                              ***
 1400 FORMAT('0',9X,'3',4X,'4',4X,'5',4X,'6',4X,'7',4X,'8',4X,'9',3X,'10    ***
     1',3X,'11',3X,'12',3X,'13',3X,'14',3X,'15',3X,'16',3X,'17',3X,'18',    ***
     23X,'19',3X,'20',3X,'21',3X,'22',3X,'23',3X,'24',3X,'25',3X,'26')      ***
 1500 FORMAT('0',8X,'27',3X,'28',3X,'29',3X,'30',3X,'31',3X,'32',3X,'33'    ***
     1,3X,'34',3X,'35',3X,'36',3X,'37',3X,'38',3X,'39',3X,'40',3X,'41',3    ***
     2X,'42',3X,'43',3X,'44',3X,'45',3X,'46',3X,'47',3X,'48',3X,'49',3X,    ***
     3'50')                                                                 ***
 1600 FORMAT('0',8X,'51',3X,'52',3X,'53',3X,'54',3X,'55',3X,'56',3X,'57'    ***
     1,3X,'58',3X,'59',3X,'60',3X,'61',3X,'62',3X,'63',3X,'64',3X,'65',3    ***
     2X,'66',3X,'67',3X,'68',3X,'69',3X,'70',3X,'71',3X,'72',3X,'73',3X,    ***
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     3'74')
 1700 FORMAT('0',3X,'75',3X,'76',3X,'77',3X,'78',3X,'79',3X,'80',3X,'81'
     1,3X,'82',3X,'83',3X,'84',3X,'85',3X,'86',3X,'87',3X,'88',3X,'89',3
     2X,'90',3X,'91',3X,'92',3X,'93',3X,'94',3X,'95',3X,'96',3X,'97',
     33X,'98')
      END


      SUBROUTINE SOLVE(PHI,STRT,OLD,T,S,TR,TC,TK,WELL,DELX,DELY,DELZ,FAC
     1T,EL,FL,GL,V,XI,TEST3,QRE,RCG,RCL,RHSS,HB)
C     ------------------------------------------------------------------
C     SOLUTION BY THE STRONGLY IMPLICIT PROCEDURE
C     ------------------------------------------------------------------
C
C     SPECIFICATIONS:
      REAL *8PHI,RHO,B,D,F,H,Z,SU,RHOP,W,WMIN,RHO1,RHO2,RHO3,XPART,YPART
     1,ZPART,DMIN1,WMAX,XT,YT,ZT,DABS,DMAX1,DEN,TXM,TYM,TZM
      REAL *8E,AL,BL,CL,A,C,G,WU,TU,U,DL,RES,SUPH,GLXI,ZPHI
C
      DIMENSION PHI(1), STRT(1), OLD(1), T(1), S(1), TR(1), TC(1), TK(1)
     1, WELL(1), DELX(1), DELY(1), DELZ(1), FACT(K0,3), RHOP(20), TEST3(
     21),EL(1),FL(1),GL(1),V(1),XI(1),QRE(1),RCG(1),RCL(1),RHSS(1),HB(1)
C
      COMMON /INTEGR/ I0,J0,K0,I1,J1,K1,I,J,K,NPER,KTH,ITMAX,LENGTH,KP,N
     1WEL,NUMT,IFINAL,IT,KT,IHEAD,IDRAW,IFLO,IERR,I2,J2,K2,IMAX,ITMX1,NC
     2H,IDK1,IDK2,IWATER,IQRE,IP,JP,IQ,JQ,IK,JK,K5,IPU1,IPU2,ITK,IEQN,KK
     3K,KKKK,IR,ISTAT,MLTCHK,ISBOUT,IJKMAP,IVHMAP,IZTOZ,ITABLE,
     4LAYDDN,ISLEAK,IOCTAP,IWLWD,IPPOUT
      COMMON /SPARAM/ TMAX,CDLT,DELT,ERR,TEST,SUM,SUMP,QR
      COMMON /SARRAY/ ICHK(13),LEVEL1(9),LEVEL2(9)
      RETURN
C     ..................................................................
C     ********************
      ENTRY ITER
C     ********************
C     ---COMPUTE AND PRINT ITERATION PARAMETERS---
      WRITE (6,240)
      WMIN=1.D0
      DELT=1.
      P2=LENGTH-1
      NIJ=I0*J0
      NT=I0*J0*K0
      XT=3.141593**2/(2.*J2*J2)
      YT=3.141593**2/(2.*I2*I2)
      ZT=3.141593**2/(2.*K0*K0)
      RHO1=0.D0
      RHO2=0.D0
      RHO3=0.D0
      DO 40 K=1,K0
      DO 40 I=2,I1
      DO 40 J=2,J1
      N=I+(J-1)*I0+(K-1)*NIJ
      IF(T(N).EQ.0.) GO TO 40
```

```
      D=TR(N-IO)/DELX(J)
      F=TR(N)/DELX(J)
      B=TC(N-1)/DELY(I)
      H=TC(N)/DELY(I)
      SU=0.D0
      Z=0.D0
C                                                                   ***
C     CORRECTION IN MANNER OF ITERATION PARAMETER COMPUTATION.      ***
C                                                                   ***
      IF(K.EQ.1) GO TO 5                                            ***
      IF(T(N-NIJ).EQ.0) GO TO 5                                     ***
      Z=TK(N-NIJ)                                                   ***
      IF(IEQN.EQ.ICHK(11)) Z=Z/DELZ(K)                              ***
    5 IF(K.EQ.KO) GO TO 10                                          ***
      IF(T(N+NIJ).EQ.0) GO TO 10                                    ***
      SU=TK(N)                                                      ***
      IF(IEQN.EQ.ICHK(11)) SU=SU/DELZ(K)                            ***
   10 CONTINUE
      TXM=DMAX1(D,F)
      TYM=DMAX1(B,H)
      TZM=DMAX1(SU,Z)
      DEN=DMIN1(D,F)
      IF (DEN.EQ.0.D0) DEN=TXM
      IF (DEN.EQ.0.D0) GO TO 20
      RHO1=DMAX1(RHO1,TYM/DEN)
   20 DEN=DMIN1(B,H)
      IF (DEN.EQ.0.D0) DEN=TYM
      IF (DEN.EQ.0.D0) GO TO 30
      RHO2=DMAX1(RHO2,TXM/DEN)
   30 DEN=DMIN1(SU,Z)
      IF (DEN.EQ.0.D0) DEN=TZM
      IF (DEN.EQ.0.D0) GO TO 40
      RHO3=DMAX1(RHO3,TXM/DEN)
   40 CONTINUE
      XPART=XT/(1.D0+RHO1)
      YPART=YT/(1.D0+RHO2)
      ZPART=ZT/(1.D0+RHO3)
      WMIN=DMIN1(WMIN,XPART,YPART,ZPART)
      WMAX=1.D0-WMIN
      PJ=-1.
      DO 50 I=1,LENGTH
      PJ=PJ+1.
   50 RHOP(I)=1.D0-(1.D0-WMAX)**(PJ/P2)
      WRITE (6,230) LENGTH,(RHOP(J),J=1,LENGTH)
      RETURN
C     ...................................................................
C
C     ---INITIALIZE DATA FOR A NEW ITERATION---
   60 IT=IT+1
      IF (IT.LE.ITMAX) GO TO 70
      WRITE (6,220)
      CALL OUTPUT
   70 IF (MOD(IT,LENGTH)) 80,80,90
```

```
C     ********************                                                SP3 920
      ENTRY NEWITA                                                        SP3 930
C     ********************                                                SP3 940
   80 NTH=0                                                               SP3 950
   90 NTH=NTH+1                                                           SP3 960
      W=RHOP(NTH)                                                         SP3 970
      TEST3(IT+1)=0.                                                      SP3 980
      TEST=0.0                                                            SP3 990
      BIG=0.                                                              SP31000
      DO 100 I=1,NT                                                       SP31010
      EL(I)=0.                                                            SP31020
      FL(I)=0.                                                            SP31030
      GL(I)=0.                                                            SP31040
      V(I)=0.                                                             SP31050
  100 XI(I)=0.                                                            SP31060
C                                                                         SP31070
C     ---COMPUTE TRANSMISSIVITY AND T COEFFICIENTS FOR UPPER              SP31080
C     HYDROLOGIC UNIT WHEN IT IS UNCONFINED---                            SP31090
      IF (IWATER.NE.ICHK(6)) GO TO 110                                    SP31100
      CALL TRANS(0)                                                       SP31110
C                                                                         SP31120
C     ---CHOOSE SIP NORMAL OR REVERSE ALGORITHM---                        SP31130
  110 IF (MOD(IT,2)) 120,120,170                                          SP31140
  120 DO 150 K=1,KO                                                       SP31150
      DO 150 I=2,I1                                                       SP31160
      DO 150 J=2,J1                                                       SP31170
      N=I+(J-1)*IO+(K-1)*NIJ                                              SP31180
      NIA=N+1                                                             SP31190
      NIB=N-1                                                             SP31200
      NJA=N+IO                                                            SP31210
      NJB=N-IO                                                            SP31220
      NKA=N+NIJ                                                           SP31230
      NKB=N-NIJ                                                           SP31240
C                                                                         SP31250
C     ---SKIP COMPUTATIONS IF NODE OUTSIDE MODEL---                       SP31260
      IF (T(N).EQ.0..OR.S(N).LT.0.) GO TO 150                             SP31270
C                                                                         SP31280
C     ---COMPUTE COEFFICIENTS---                                          SP31290
      D=TR(NJB)/DELX(J)                                                   SP31300
      F=TR(N)/DELX(J)                                                     SP31310
      B=TC(NIB)/DELY(I)                                                   SP31320
      H=TC(N)/DELY(I)                                                     SP31330
      SU=0.D0                                                             SP31340
      Z=0.D0                                                              SP31350
      IF(K.EQ.1) GO TO 124                                                SP31361
      Z=TK(NKB)                                                           SP31362
      IF(IEQN.EQ.ICHK(11)) Z=Z/DELZ(K)                                    SP31363
  124 IF(K.EQ.KO) GO TO 125                                               SP31371
      SU=TK(N)                                                            SP31372
      IF(IEQN.EQ.ICHK(11))SU=SU/DELZ(K)                                   SP31373
  125 RHO=S(N)/DELT                                                       SP31380
      QR=0.                                                               SP31390
      IF (K.NE.KO) GO TO 130                                              SP31400
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```
      IF (IQRE.EQ.ICHK(7)) QR=QRE(I+(J-1)*I0)                           SP31410
C                                                                       SP31420
C     ---SIP NORMAL ALGORITHM---                                        SP31430
C     ---FORWARD SUBSTITUTE, COMPUTING INTERMEDIATE VECTOR V---         SP31440
C                                                                         ***
C     ALL FOLLOWING CHANGES IN SOLVE SUBROUTINE                           ***
C     FOR HEAD DEPENDENT STREAM OPTION.                                   ***
C                                                                         ***
  130 IF(PHI(N).GE.RHSS(N)) E=-B-D-F-H-SU-Z-RHO-RCG(N)                    ***
      IF(PHI(N).LT.RHSS(N)) E=-B-D-F-H-SU-Z-RHO-RCL(N)                    ***
      BL=B/(1.+W*(EL(NIB)+GL(NIB)))                                     SP31460
      CL=D/(1.+W*(FL(NJB)+GL(NJB)))                                     SP31470
      C=BL*EL(NIB)                                                      SP31480
      G=CL*FL(NJB)                                                      SP31490
      WU=CL*GL(NJB)                                                     SP31500
      U=BL*GL(NIB)                                                      SP31510
      IF (K.EQ.1) GO TO 140                                             SP31520
      AL=Z/(1.+W*(EL(NKB)+FL(NKB)))                                     SP31530
      A=AL*EL(NKB)                                                      SP31540
      TU=AL*FL(NKB)                                                     SP31550
      DL=E+W*(A+C+G+WU+TU+U)-CL*EL(NJB)-BL*FL(NIB)-AL*GL(NKB)           SP31560
      EL(N)=(F-W*(A+C))/DL                                              SP31570
      FL(N)=(H-W*(G+TU))/DL                                             SP31580
      GL(N)=(SU-W*(WU+U))/DL                                            SP31590
      SUPH=0.D0                                                         SP31600
      IF (K.NE.K0) SUPH=SU*PHI(NKA)                                     SP31610
      IF(PHI(N).GE.RHSS(N)) RES=-B*PHI(NIB)-D*PHI(NJB)-E*PHI(N)-F*PHI(NJ  ***
     1A)-H*PHI(NIA)-SUPH-Z*PHI(NKB)-WELL(N)-RHO*OLD(N)-QR-RCG(N)*RHSS(N)  ***
      IF(PHI(N).LT.RHSS(N)) RES=-B*PHI(NIB)-D*PHI(NJB)-E*PHI(N)-F*PHI(NJ  ***
     1A)-H*PHI(NIA)-SUPH-Z*PHI(NKB)-WELL(N)-RHO*OLD(N)-QR-RCL(N)*RHSS(N)  ***
      IF(PHI(N).LT.HB(N)) RES=RES+RCL(N)*HB(N)-RCL(N)*PHI(N)              ***
      V(N)=(RES-AL*V(NKB)-BL*V(NIB)-CL*V(NJB))/DL                       SP31640
      GO TO 150                                                         SP31650
  140 DL=E+W*(C+G+WU+U)-CL*EL(NJB)-BL*FL(NIB)                           SP31660
      EL(N)=(F-W*C)/DL                                                  SP31670
      FL(N)=(H-W*G)/DL                                                  SP31680
      GL(N)=(SU-W*(WU+U))/DL                                            SP31690
      SUPH=0.D0                                                         SP31700
      IF (K.NE.K0) SUPH=SU*PHI(NKA)                                     SP31710
      IF(PHI(N).GE.RHSS(N)) RES=-B*PHI(NIB)-D*PHI(NJB)-E*PHI(N)-F*PHI(NJ  ***
     1A)-H*PHI(NIA)-SUPH-WELL(N)-RHO*OLD(N)-QR-RCG(N)*RHSS(N)             ***
      IF(PHI(N).LT.RHSS(N)) RES=-B*PHI(NIB)-D*PHI(NJB)-E*PHI(N)-F*PHI(NJ  ***
     1A)-H*PHI(NIA)-SUPH-WELL(N)-RHO*OLD(N)-QR-RCL(N)*RHSS(N)             ***
      IF(PHI(N).LT.HB(N)) RES=RES+RCL(N)*HB(N)-RCL(N)*PHI(N)              ***
      V(N)=(RES-BL*V(NIB)-CL*V(NJB))/DL                                 SP31740
  150 CONTINUE                                                          SP31750
C                                                                       SP31760
C     ---BACK SUBSTITUTE FOR VECTOR XI---                               SP31770
      DO 160 K=1,K0                                                     SP31780
      K3=K0-K+1                                                         SP31790
      DO 160 I=1,I2                                                     SP31800
      I3=I0-I                                                           SP31810
      DO 160 J=1,J2                                                     SP31820
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      J3=J0-J                                                           SP31830
      N=I3+(J3-1)*I0+(K3-1)*NIJ+I-I                                     SP31840
      IF (T(N).EQ.0..OR.S(N).LT.0.) GO TO 160                           SP31850
      GLXI=0.D0                                                         SP31860
      IF (K3.NE.K0) GLXI=GL(N)*XI(N+NIJ)                                SP31870
      XI(N)=V(N)-EL(N)*XI(N+I0)-FL(N)*XI(N+1)-GLXI                      SP31880
C                                                                       SP31890
C     ---COMPARE MAGNITUDE OF CHANGE WITH CLOSURE CRITERIA---           SP31900
      TCHK=ABS(XI(N))                                                   SP31910
      IF (TCHK.GT.BIG) BIG=TCHK                                         SP31920
      PHI(N)=PHI(N)+XI(N)                                               SP31930
  160 CONTINUE                                                          SP31940
      IF (BIG.GT.ERR) TEST=1.                                           SP31950
      TEST3(IT+1)=BIG                                                   SP31960
      IF (TEST.EQ.0.) RETURN                                            SP31970
      GO TO 60                                                          SP31980
C     ..................................................................SP31990
  170 DO 200 KK=1,K0                                                    SP32000
      K=K0-KK+1                                                         SP32010
      DO 200 II=1,I2                                                    SP32020
      I=I0-II                                                           SP32030
      DO 200 J=2,J1                                                     SP32040
      N=I+(J-1)*I0+(K-1)*NIJ                                            SP32050
      NIA=N+1                                                           SP32060
      NIB=N-1                                                           SP32070
      NJA=N+I0                                                          SP32080
      NJB=N-I0                                                          SP32090
      NKA=N+NIJ                                                         SP32100
      NKB=N-NIJ                                                         SP32110
C                                                                       SP32120
C     ---SKIP COMPUTATIONS IF NODE OUTSIDE AQUIFER---                   SP32130
      IF (T(N).EQ.0..OR.S(N).LT.0.) GO TO 200                           SP32140
C                                                                       SP32150
C     ---COMPUTE COEFFICIENTS---                                        SP32160
      D=TR(NJB)/DELX(J)                                                 SP32170
      F=TR(N)/DELX(J)                                                   SP32180
      B=TC(NIB)/DELY(I)                                                 SP32190
      H=TC(N)/DELY(I)                                                   SP32200
      SU=0.D0                                                           SP32210
      Z=0.D0                                                            SP32220
      IF(K.EQ.1) GO TO 174                                              SP32231
      Z=TK(NKB)                                                         SP32232
      IF(IEQN.EQ.ICHK(11)) Z=Z/DELZ(K)                                  SP32233
  174 IF(K.EQ.K0) GO TO 175                                             SP32241
      SU=TK(N)                                                          SP32242
      IF(IEQN.EQ.ICHK(11))SU=SU/DELZ(K)                                 SP32243
  175 RHO=S(N)/DELT                                                     SP32250
      QR=0.                                                             SP32260
      IF (K.NE.K0) GO TO 180                                            SP32270
      IF (IQRE.EQ.ICHK(7)) QR=QRE(I+(J-1)*I0)                           SP32280
C                                                                       SP32290
C     ---SIP REVERSE ALGORITHM---                                       SP32300
C     ---FORWARD SUBSTITUTE, COMPUTING INTERMEDIATE VECTOR V---         SP32310
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  180 IF(PHI(N).GE.RHSS(N)) E=-B-D-F-H-SU-Z-RHO-RCG(N)                    ***
      IF(PHI(N).LT.RHSS(N)) E=-B-D-F-H-SU-Z-RHO-RCL(N)                    ***
      BL=H/(1.+W*(EL(NIA)+GL(NIA)))                                      SP32330
      CL=D/(1.+W*(FL(NJB)+GL(NJB)))                                      SP32340
      C=BL*EL(NIA)                                                       SP32350
      G=CL*FL(NJB)                                                       SP32360
      WU=CL*GL(NJB)                                                      SP32370
      U=BL*GL(NIA)                                                       SP32380
      IF (K.EQ.KO) GO TO 190                                             SP32390
      AL=SU/(1.+W*(EL(NKA)+FL(NKA)))                                     SP32400
      A=AL*EL(NKA)                                                       SP32410
      TU=AL*FL(NKA)                                                      SP32420
      DL=E+W*(C+G+A+WU+TU+U)-AL*GL(NKA)-BL*FL(NIA)-CL*EL(NJB)            SP32430
      EL(N)=(F-W*(C+A))/DL                                               SP32440
      FL(N)=(B-W*(G+TU))/DL                                              SP32450
      GL(N)=(Z-W*(WU+U))/DL                                              SP32460
      ZPHI=0.D0                                                          SP32470
      IF (K.NE.1) ZPHI=Z*PHI(NKB)                                        SP32480
      IF(PHI(N).GE.RHSS(N)) RES=-B*PHI(NIB)-D*PHI(NJB)-E*PHI(N)-F*PHI(NJ  ***
     1A)-H*PHI(NIA)-SU*PHI(NKA)-ZPHI-WELL(N)-RHO*OLD(N)-QR-RCG(N)*RHSS(N  ***
     2)                                                                   ***
      IF(PHI(N).LT.RHSS(N)) RES=-B*PHI(NIB)-D*PHI(NJB)-E*PHI(N)-F*PHI(NJ  ***
     1A)-H*PHI(NIA)-SU*PHI(NKA)-ZPHI-WELL(N)-RHO*OLD(N)-QR-RCL(N)*RHSS(N  ***
     2)                                                                   ***
      IF(PHI(N).LT.HB(N)) RES=RES+RCL(N)*HB(N)-RCL(N)*PHI(N)              ***
      V(N)=(RES-AL*V(NKA)-BL*V(NIA)-CL*V(NJB))/DL                        SP32510
      GO TO 200                                                          SP32520
  190 DL=E+W*(C+G+WU+U)-BL*FL(NIA)-CL*EL(NJB)                            SP32530
      EL(N)=(F-W*C)/DL                                                   SP32540
      FL(N)=(B-W*G)/DL                                                   SP32550
      GL(N)=(Z-W*(WU+U))/DL                                              SP32560
      ZPHI=0.D0                                                          SP32570
      IF (K.NE.1) ZPHI=Z*PHI(NKB)                                        SP32580
      IF(PHI(N).GE.RHSS(N)) RES=-B*PHI(NIB)-D*PHI(NJB)-E*PHI(N)-F*PHI(NJ  ***
     1A)-H*PHI(NIA)-ZPHI-WELL(N)-RHO*OLD(N)-QR-RCG(N)*RHSS(N)             ***
      IF(PHI(N).LT.RHSS(N)) RES=-B*PHI(NIB)-D*PHI(NJB)-E*PHI(N)-F*PHI(NJ  ***
     1A)-H*PHI(NIA)-ZPHI-WELL(N)-RHO*OLD(N)-QR-RCL(N)*RHSS(N)             ***
      IF(PHI(N).LT.HB(N)) RES=RES+RCL(N)*HB(N)-RCL(N)*PHI(N)              ***
      V(N)=(RES-BL*V(NIA)-CL*V(NJB))/DL                                  SP32610
  200 CONTINUE                                                           SP32620
C                                                                        SP32630
C     ---BACK SUBSTITUTE FOR VECTOR XI---                                SP32640
      DO 210 K=1,KO                                                      SP32650
      DO 210 I=2,I1                                                      SP32660
      DO 210 J=1,J2                                                      SP32670
      J3=J0-J                                                            SP32680
      N=I+(J3-1)*I0+(K-1)*NIJ                                            SP32690
      IF (T(N).EQ.0..OR.S(N).LT.0.) GO TO 210                            SP32700
      GLXI=0.D0                                                          SP32710
      IF (K.NE.1) GLXI=GL(N)*XI(N-NIJ)                                   SP32720
      XI(N)=V(N)-EL(N)*XI(N+I0)-FL(N)*XI(N-1)-GLXI                       SP32730
C                                                                        SP32740
C     ---COMPARE MAGNITUDE OF CHANGE WITH CLOSURE CRITERIA---            SP32750
```

```
      TCHK=ABS(XI(N))
      IF (TCHK.GT.BIG) BIG=TCHK
      PHI(N)=PHI(N)+XI(N)
  210 CONTINUE
      IF (BIG.GT.ERR) TEST=1.
      TEST3(IT+1)=BIG
      IF (TEST.EQ.0.) RETURN
      GO TO 60
C     ...................................................................
C
C     ---FORMATS---
C
C
C
  220 FORMAT ('0EXCEEDED PERMITTED NUMBER OF ITERATIONS'/' ',39('*'))
  230 FORMAT (///1H0,I5,22H ITERATION PARAMETERS:,6E15.7/(/28X,6E15.7/))
  240 FORMAT ('-',44X,'SOLUTION BY THE STRONGLY IMPLICIT PROCEDURE'/45X,
     143('_'))
      END


      SUBROUTINE COEF(PHI,STRT,OLD,T,S,TR,TC,TK,WELL,DELX,DELY,DELZ,FACT
     1,PERM,BOTTOM,QRE,IZN,KXU,KYU,KZU,BZU,SZU,KXL,KYL,KZL,BZL,SZL,
     2 PMULT,NZNS)
C     ------------------------------------------------------------------
C     COMPUTE COEFFICIENTS
C     ------------------------------------------------------------------
C
C     SPECIFICATIONS:
      REAL *8PHI
      REAL KXU,KYU,KZU,KXL,KYL,KZL
C
      DIMENSION PHI(I0,J0,K0), STRT(I0,J0,K0), OLD(I0,J0,K0), T(I0,J0,K0
     1), S(I0,J0,K0), TR(I0,J0,K0), TC(I0,J0,K0), TK(IK,JK,K5), WELL(I0,
     2J0,K0), DELX(J0), DELY(I0), DELZ(K0), FACT(K0,3), PERM(IP,JP), BOT
     3TOM(IP,JP),QRE(IQ,JQ),PMULT(25,5),PKXU(68,100),PKYU(68,100),PKZU(6
     48,100),PKXL(68,100),PKYL(68,100),PKZL(68,100)
      DIMENSION IZN(I0,J0),KXU(1),KYU(1),KZU(1),BZU(1),SZU(1),
     1 KXL(1),KYL(1),KZL(1),BZL(1),SZL(1)
C
      COMMON /INTEGR/ I0,J0,K0,I1,J1,K1,I,J,K,NPER,KTH,ITMAX,LENGTH,KP,N
     1WEL,NUMT,IFINAL,IT,KT,IHEAD,IDRAW,IFLO,IERR,I2,J2,K2,IMAX,ITMX1,NC
     2H,IDK1,IDK2,IWATER,IQRE,IP,JP,IQ,JQ,IK,JK,K5,IPU1,IPU2,ITK,IEQN,KK
     3K,KKKK,IR,ISTAT,MLTCHK,ISBOUT,IJKMAP,IVHMAP,IZTOZ,ITABLE,
     4LAYDDN,ISLEAK,IOCTAP,IWLWD,IPPOUT
      COMMON /SPARAM/ TMAX,CDLT,DELT,ERR,TEST,SUM,SUMP,QR
      COMMON /SARRAY/ ICHK(13),LEVEL1(9),LEVEL2(9)
      RETURN
      ENTRY INPUT
      DO 100 I=1,I0
      DO 100 J=1,J0
      PKXL(I,J)=0.
      PKYL(I,J)=0.
```

```
      PKZL(I,J)=0.                                                      ***
      PKXU(I,J)=0.                                                      ***
      PKYU(I,J)=0.                                                      ***
  100 PKZU(I,J)=0.                                                      ***
C                                                                       ***
C     READ AQUIFER ZONATION AND VALUES FOR EACH ZONE                    ***
C                                                                       ***
      WRITE(6,9005)                                                     ***
      DO 9000 I=1,I0                                                    ***
      READ 9010,(IZN(I,J),J=1,J0)                                       ***
 9000 PRINT 9020,I,(IZN(I,J),J=1,J0)                                    ***
 9005 FORMAT('0','ZONATION SCHEME')                                     ***
 9010 FORMAT(40I2)                                                      ***
 9020 FORMAT(/,1X,I2,2X,3(/40I3))                                       ***
      WRITE(6,9035)                                                     ***
      DO 9030 K=1,NZNS                                                  ***
      READ 9010,N                                                       ***
      READ 9040,KXL(N),KYL(N),KZL(N),BZL(N),SZL(N)                      ***
      READ 9040,KXU(N),KYU(N),KZU(N),BZU(N),SZU(N)                      ***
      PRINT 9050,N,KXL(N),KYL(N),KZL(N),BZL(N),SZL(N)                   ***
 9030 PRINT 9060,N,KXU(N),KYU(N),KZU(N),BZU(N),SZU(N)                   ***
C                                                                       ***
C     MODIFICATION OF HYDRAULIC CONDUCTIVITY BASED                      ***
C     ON TOPOGRAPHIC SETTING.                                           ***
C                                                                       ***
      DO 9031 I=1,NZNS                                                  ***
 9031 READ(5,9070) (PMULT(I,J),J=1,5)                                   ***
      WRITE(6,9075)                                                     ***
      WRITE(6,9080)                                                     ***
      WRITE(6,9083)                                                     ***
      DO 9032 I=1,NZNS                                                  ***
 9032 WRITE(6,9085) I,(PMULT(I,J),J=1,5)                                ***
      DO 9033 I=2,I1                                                    ***
      DO 9033 J=2,J1                                                    ***
      DO 9034 LLL=1,NZNS                                                ***
      IF(IZN(I,J).EQ.0) GO TO 9033                                      ***
      IF(IZN(I,J).EQ.LLL) GO TO 9036                                    ***
      GO TO 9034                                                        ***
 9036 IF(PERM(I,J).EQ.0.) GO TO 9034                                    ***
      IF(PERM(I,J).EQ.1.) GO TO 9037                                    ***
      GO TO 9038                                                        ***
 9037 PKXU(I,J)=PMULT(LLL,1)*KXU(LLL)                                   ***
      PKYU(I,J)=PMULT(LLL,1)*KYU(LLL)                                   ***
      PKZU(I,J)=PMULT(LLL,1)*KZU(LLL)                                   ***
      PKXL(I,J)=PMULT(LLL,1)*KXL(LLL)                                   ***
      PKYL(I,J)=PMULT(LLL,1)*KYL(LLL)                                   ***
      PKZL(I,J)=PMULT(LLL,1)*KZL(LLL)                                   ***
      GO TO 9033                                                        ***
 9038 IF(PERM(I,J).EQ.2.) GO TO 9039                                    ***
      GO TO 9041                                                        ***
 9039 PKXU(I,J)=PMULT(LLL,2)*KXU(LLL)                                   ***
      PKYU(I,J)=PMULT(LLL,2)*KYU(LLL)                                   ***
      PKZU(I,J)=PMULT(LLL,2)*KZU(LLL)                                   ***
```

```
      PKXL(I,J)=PMULT(LLL,2)*KXL(LLL)                                        ***
      PKYL(I,J)=PMULT(LLL,2)*KYL(LLL)                                        ***
      PKZL(I,J)=PMULT(LLL,2)*KZL(LLL)                                        ***
      GO TO 9033                                                             ***
 9041 IF(PERM(I,J).EQ.3.) GO TO 9042                                         ***
      GO TO 9043                                                             ***
 9042 PKXU(I,J)=PMULT(LLL,3)*KXU(LLL)                                        ***
      PKYU(I,J)=PMULT(LLL,3)*KYU(LLL)                                        ***
      PKZU(I,J)=PMULT(LLL,3)*KZU(LLL)                                        ***
      PKXL(I,J)=PMULT(LLL,3)*KXL(LLL)                                        ***
      PKYL(I,J)=PMULT(LLL,3)*KYL(LLL)                                        ***
      PKZL(I,J)=PMULT(LLL,3)*KZL(LLL)                                        ***
      GO TO 9033                                                             ***
 9043 IF(PERM(I,J).EQ.4.) GO TO 9044                                         ***
      GO TO 9045                                                             ***
 9044 PKXU(I,J)=PMULT(LLL,4)*KXU(LLL)                                        ***
      PKYU(I,J)=PMULT(LLL,4)*KYU(LLL)                                        ***
      PKZU(I,J)=PMULT(LLL,4)*KZU(LLL)                                        ***
      PKXL(I,J)=PMULT(LLL,4)*KXL(LLL)                                        ***
      PKYL(I,J)=PMULT(LLL,4)*KYL(LLL)                                        ***
      PKZL(I,J)=PMULT(LLL,4)*KZL(LLL)                                        ***
      GO TO 9033                                                             ***
 9045 IF(PERM(I,J).EQ.5.) GO TO 9046                                         ***
 9046 PKXU(I,J)=PMULT(LLL,5)*KXU(LLL)                                        ***
      PKYU(I,J)=PMULT(LLL,5)*KYU(LLL)                                        ***
      PKZU(I,J)=PMULT(LLL,5)*KZU(LLL)                                        ***
      PKXL(I,J)=PMULT(LLL,5)*KXL(LLL)                                        ***
      PKYL(I,J)=PMULT(LLL,5)*KYL(LLL)                                        ***
      PKZL(I,J)=PMULT(LLL,5)*KZL(LLL)                                        ***
      GO TO 9033                                                             ***
 9034 CONTINUE                                                               ***
 9033 CONTINUE                                                               ***
      IF(MLTCHK.EQ.0) GO TO 9048                                             ***
      WRITE(6,9090)                                                          ***
      WRITE(6,9095) (PKXU(10,J),J=1,J0)                                      ***
      WRITE(6,9095) (PKYU(10,J),J=1,J0)                                      ***
      WRITE(6,9095) (PKZU(10,J),J=1,J0)                                      ***
      WRITE(6,9095) (PKXL(10,J),J=1,J0)                                      ***
      WRITE(6,9095) (PKYL(10,J),J=1,J0)                                      ***
      WRITE(6,9095) (PKZL(10,J),J=1,J0)                                      ***
 9090 FORMAT('1',1X,'PRINTOUT OF PKXU,PKYU,PKZU,PKXL,PKYL,PKZL VALUES        ***
     1FOR ROW 10')                                                           ***
 9095 FORMAT('0',4X,10E11.3/(5X,10E11.3))                                    ***
 9048 CONTINUE                                                               ***
 9035 FORMAT('1',3X,'LAYER',4X,'ZONE',6X,'KX',9X,'KY',9X,'KZ',5X,'THICKN     ***
     1ESS',3X,'STORAGE')                                                     ***
 9040 FORMAT(8F10.0)                                                         ***
 9050 FORMAT(/,5X,'1',5X,I4,2X,7(1X,1PE10.3))                                ***
 9060 FORMAT(/,5X,'2',5X,I4,2X,7(1X,1PE10.3))                                ***
 9070 FORMAT(5F5.1)                                                          ***
 9075 FORMAT('1',10X,'PERMEABILITY MULTIPLIERS')                             ***
 9080 FORMAT('0',16X,'AVERAGE BLOCK TOPOGRAPHY')                             ***
 9083 FORMAT('0',4X,'ZONE',6X,'1',6X,'2',6X,'3',6X,'4',6X,'5')               ***
```

```
 9085 FORMAT('0',5X,I2,6X,F3.1,4X,F3.1,4X,F3.1,4X,F3.1,4X,F3.1)          ***
      RETURN                                                            ***
C     ..................................................................COF 210
C     ---COMPUTE TRANSMISSIVITY FOR UPPER HYDROLOGIC UNIT WHEN          COF 220
C     IT IS UNCONFINED---                                               COF 230
C     ********************                                              COF 240
      ENTRY TRANS                                                       ***
C     ********************                                              COF 260
      DO 10 J=2,J1                                                      ***
      DO 10 I=2,I1                                                      COF 270
      N=IZN(I,J)                                                        ***
      IF(N.LE.0) GO TO 10                                               ***
      THICK=PHI(I,J,KO)-BOTTOM(I,J)                                     ***
      IF(THICK.GT.0.) GO TO 5                                           ***
      IF(T(I,J,KO).EQ.0.) GO TO 10                                      ***
      IF (WELL(I,J,KO).LT.0.) WRITE (6,60) I,J,KO                       COF 320
      IF (WELL(I,J,KO).GE.0.) WRITE (6,70) I,J,KO                       COF 330
      T(I,J,KO)=0.                                                      COF 350
      TR(I,J-1,KO)=0.                                                   COF 360
      TR(I,J,KO)=0.                                                     COF 370
      TC(I,J,KO)=0.                                                     COF 380
      TC(I-1,J,KO)=0.                                                   COF 390
      IF (KO.NE.1) TK(I,J,K1)=0.                                        COF 400
      PHI(I,J,KO)=BOTTOM(I,J)                                           ***
      S(I,J,1)=S(I,J,2)                                                 ***
      GO TO 10                                                          ***
    5 CONTINUE                                                          ***
C                                                                       ***
C     COMPUTATIONS OF TR AND TC MODIFIED TO INCORPORATE                 ***
C     REVISED HYDRAULIC CONDUCTIVITY.                                   ***
C                                                                       ***
C     I+1 OR TC DIRECTION                                               ***
C                                                                       ***
      N1=IZN(I+1,J)                                                     ***
      IF(N1.LE.0) GO TO 6                                               ***
      IF(PKYU(I+1,J).LE.0.) GO TO 6                                     ***
      THICK1=PHI(I+1,J,KO)-BOTTOM(I+1,J)                                ***
      IF(THICK1.LE.0.) GO TO 6                                          ***
      T1=THICK*PKYU(I,J)                                                ***
      T2=THICK1*PKYU(I+1,J)                                             ***
      IF(T1.EQ.0..AND.T2.EQ.0.) GO TO 6                                 ***
      TC(I,J,2)=2.*T1*T2/(T1*DELY(I+1)+T2*DELY(I))                      ***
C                                                                       ***
C     J+1 OR TR DIRECTION                                               ***
C                                                                       ***
    6 N1=IZN(I,J+1)                                                     ***
      IF(N1.LE.0) GO TO 10                                              ***
      IF(PKXU(I,J+1).LE.0.) GO TO 10                                    ***
      THICK1=PHI(I,J+1,KO)-BOTTOM(I,J+1)                                ***
      IF(THICK1.LE.0.) GO TO 10                                         ***
      T1=THICK*PKXU(I,J)                                                ***
      T2=THICK1*PKXU(I,J+1)                                             ***
      IF(T1.EQ.0..AND.T2.EQ.0.) GO TO 10                                ***
```

```
      TR(I,J,2)=2.*T1*T2/(T1*DELX(J+1)+T2*DELX(J))                        ***
   10 CONTINUE                                                          COF 420
      RETURN                                                              ***
C     ---COMPUTE T COEFFICIENTS---                                      COF 480
C     *********************                                             COF 490
      ENTRY TCOF                                                        COF 500
C     *********************                                             COF 510
      DO 8000 J=1,J0                                                      ***
      DO 8000 I=1,I0                                                      ***
      N=IZN(I,J)                                                          ***
      T(I,J,1)=0.                                                         ***
      T(I,J,2)=0.                                                         ***
      IF(N.LE.0) GO TO 8000                                               ***
      T(I,J,1)=PKXL(I,J)*BZL(N)                                           ***
      T(I,J,2)=PKXU(I,J)*BZU(N)                                           ***
      IF(S(I,J,1).GE.0.) S(I,J,1)=SZL(N)                                  ***
      IF(S(I,J,2).GE.0.) S(I,J,2)=SZU(N)                                  ***
 8000 CONTINUE                                                            ***
C                                                                         ***
C     COMPUTE TR, TC, AND TK COEFFICIENTS                                 ***
C                                                                         ***
      DO 8010 J=1,J1                                                      ***
      DO 8010 I=1,I1                                                      ***
      N=IZN(I,J)                                                          ***
      IF(N.LE.0) GO TO 8010                                               ***
      T1=T(I,J,1)                                                         ***
      T2=T(I,J+1,1)                                                       ***
      IF(T1.EQ.0..AND.T2.EQ.0.) GO TO 20                                  ***
      TR(I,J,1)=2.*T1*T2/(T1*DELX(J+1)+T2*DELX(J))                        ***
   20 T1=T(I,J,2)                                                         ***
      T2=T(I,J+1,2)                                                       ***
      IF(T1.EQ.0..AND.T2.EQ.0.) GO TO 25                                  ***
      TR(I,J,2)=2.*T1*T2/(T1*DELX(J+1)+T2*DELX(J))                        ***
   25 N1=IZN(I+1,J)                                                       ***
      IF(N1.LE.0) GO TO 40                                                ***
      IF(PKYU(I+1,J).LE.0.) GO TO 40                                      ***
      T1=PKYL(I,J)*BZL(N)                                                 ***
      T2=PKYL(I+1,J)*BZL(N1)                                              ***
      IF(T1.EQ.0..AND.T2.EQ.0.) GO TO 30                                  ***
      TC(I,J,1)=2.*T1*T2/(T1*DELY(I+1)+T2*DELY(I))                        ***
   30 T1=PKYU(I,J)*BZU(N)                                                 ***
      T2=PKYU(I+1,J)*BZU(N1)                                              ***
      IF(T1.EQ.0..AND.T2.EQ.0.) GO TO 40                                  ***
      TC(I,J,2)=2.*T1*T2/(T1*DELY(I+1)+T2*DELY(I))                        ***
   40 IF(KZL(N).EQ.0..AND.PKZU(I,J).EQ.0.) GO TO 8010                     ***
 8005 TK(I,J,1)=2.*PKZL(I,J)*PKZU(I,J)/(PKZL(I,J)*BZU(N)+PKZU(I,J)*BZL(N  ***
     1))                                                                  ***
 8010 CONTINUE                                                            ***
      RETURN                                                            COF 750
C                                                                       COF 760
C                                                                       COF 770
   60 FORMAT ('-',20('*'),'WELL',2I3,' IN LAYER',I3,' GOES DRY',20('*'))COF 780
   70 FORMAT ('-',20('*'),'NODE',2I3,' IN LAYER',I3,' GOES DRY',20('*'))COF 790
      END                                                               COF 800
```

```
      SUBROUTINE CHECKI(PHI,STRT,OLD,T,S,TR,TC,TK,WELL,DELX,DELY,DELZ,FA
     1CT,JFLO,FLOW,QRE,RCG,RCL,RHSS,HB,IZN,NZNS)
C     ------------------------------------------------------------------
C     COMPUTE A VOLUMETRIC BALANCE
C     ------------------------------------------------------------------
C
C     SPECIFICATIONS:
      REAL *8PHI
C
      DIMENSION PHI(IO,JO,KO), STRT(IO,JO,KO), OLD(IO,JO,KO), T(IO,JO,KO
     1), S(IO,JO,KO), TR(IO,JO,KO), TC(IO,JO,KO), TK(IK,JK,K5), WELL(IO,
     2JO,KO), DELX(JO), DELY(IO), DELZ(KO), FACT(KO,3), JFLO(NCH,3), FLO
     3W(NCH),QRE(IQ,JQ),RCG(IO,JO,KO),RCL(IO,JO,KO),RHSS(IO,JO,KO),
     4HB(IO,JO,KO)
      DIMENSION IZN(IO,JO),ZINSUM(25),ZOUTSM(25)
      DIMENSION RESID(2,25),ARESID(2,25),NCOUNT(2,25),XMAX(2,25),XMIN(2,
     125),RESID2(2,25)
      DIMENSION VFDOWN(25),VFUP(25)
      DIMENSION STORAG(2,25),RECHQ(25),X1STOT(25),X2STOT(25),
     1X1DTOT(25),X2DTOT(25),SDDIFF(25),PCDIFF(25),BDYQ(2,25)
      DIMENSION STRLK (68,100),OCT1(68,100),OCT2(68,100)
C
      COMMON /INTEGR/ IO,JO,KO,I1,J1,K1,I,J,K,NPER,KTH,ITMAX,LENGTH,KP,N
     1WEL,NUMT,IFINAL,IT,KT,IHEAD,IDRAW,IFLO,IERR,I2,J2,K2,IMAX,ITMX1,NC
     2H,IDK1,IDK2,IWATER,IQRE,IP,JP,IQ,JQ,IK,JK,K5,IPU1,IPU2,ITK,IEQN,KK
     3K,KKKK,IR,ISTAT,MLTCHK,ISBOUT,IJKMAP,IVHMAP,IZTOZ,ITABLE,
     4LAYDDN,ISLEAK,IOCTAP,IWLWD,IPPOUT
      COMMON /SPARAM/ TMAX,CDLT,DELT,ERR,TEST,SUM,SUMP,QR
      COMMON /SARRAY/ ICHK(13),LEVEL1(9),LEVEL2(9)
      COMMON /CK/ ETFLXT,STORT,QRET,CHST,CHDT,FLUXT,PUMPT,CFLUXT,FLXNT
      RETURN
C     ..................................................................
C     ********************
      ENTRY CHECK
C     ********************
C     ---INITIALIZE VARIABLES---
      PUMP=0.
      STOR=0.
      FLUXS=0.0
      CHD1=0.0
      CHD2=0.0
      QREFLX=0.
      CFLUX=0.
      FLUX=0.
      ETFLUX=0.
      FLXN=0.0
      II=0
C
C     HEAD DEPENDENT STREAM OPTION ADDITIONS.
C
      RFLOUT=0.
      RFLIN=0.
      KKK=KKK+1
```

```
      KKKK=KKKK+1                                                        ***
C     ..............................................................CHK 380
C                                                                   CHK 390
C     ---COMPUTE RATES,STORAGE AND PUMPAGE FOR THIS STEP---         CHK 400
      IF(IR.NE.1) GO TO 5                                                ***
      IF(KKK.NE.NUMT.AND.KKKK.NE.KTH) GO TO 5                            ***
      IF(ISBOUT.NE.1) GO TO 3                                            ***
      WRITE(6,300)                                                       ***
      WRITE(6,305)                                                       ***
    3 KKKK=0                                                             ***
      KKK=0                                                              ***
C                                                                        ***
C     STREAM/AQUIFER FLOW OUTPUT BY ZONE OPTION.                         ***
C                                                                        ***
    5 DO 1 I=1,NZNS                                                      ***
      ZINSUM(I)=0.                                                       ***
    1 ZOUTSM(I)=0.                                                       ***
C                                                                        ***
C     OPTION TO WRITE DRAWDOWN AND STREAM/AQUIFER FLOW                   ***
C     ON FILE FOR EACH GRID BLOCK.                                       ***
C                                                                        ***
      IF(ISLEAK.NE.1) GO TO 8                                            ***
      DO 6 I=1,IO                                                        ***
      DO 6 J=1,JO                                                        ***
    6 STRLK(I,J)=0.                                                      ***
    8 MMM=2                                                              ***
      IF(LAYDDN.NE.1) GO TO 18                                           ***
      DO 7 I=1,IO                                                        ***
      DO 7 J=1,JO                                                        ***
      IF(IZN(I,J).EQ.0) GO TO 7                                          ***
      DRAW1=STRT(I,J,1)-PHI(I,J,1)                                       ***
      DRAW2=STRT(I,J,2)-PHI(I,J,2)                                       ***
      WRITE(11,2050)I,J,IZN(I,J),DRAW1,DRAW2                             ***
    7 CONTINUE                                                           ***
C                                                                        ***
C     OPTION TO WRITE TRANSIENT HEAD CHANGE ON FILE.                     ***
C                                                                        ***
   18 IF(IOCTAP.EQ.0) GO TO 16                                           ***
      IF(IOCTAP.EQ.1) NF=13                                              ***
      IF(IOCTAP.EQ.2) NF=14                                              ***
      IF(KP.NE.4.OR.KT.NE.NUMT)  GO TO 14                                ***
      DO 13 I=1,IO                                                       ***
      DO 13 J=1,JO                                                       ***
      IF(IZN(I,J).EQ.0) GO TO 13                                         ***
      OCT1(I,J)=PHI(I,J,1)                                               ***
      OCT2(I,J)=PHI(I,J,2)                                               ***
   13 CONTINUE                                                           ***
   14 IF(KP.NE.10.OR.KT.NE.NUMT)  GO TO 16                               ***
      DO 15 I=1,IO                                                       ***
      DO 15 J=1,JO                                                       ***
      IF(IZN(I,J).EQ.0) GO TO 15                                         ***
      DRAW1=PHI(I,J,1)-OCT1(I,J)                                         ***
      DRAW2=PHI(I,J,2)-OCT2(I,J)                                         ***
```

```
      WRITE(NF,2050) I,J,IZN(I,J),DRAW1,DRAW2                           ***
   15 CONTINUE                                                          ***
   16 DO 220 K=1,K0                                                     ***
      DO 220 I=2,I1                                                   CHK 420
      DO 220 J=2,J1                                                   CHK 430
      IF (T(I,J,K).EQ.0.) GO TO 220                                   CHK 440
      AREA=DELX(J)*DELY(I)                                            CHK 450
      VOLUME=AREA*DELZ(K)                                             CHK 455
      IF (S(I,J,K).GE.0.) GO TO 180                                   CHK 460
C                                                                     CHK 470
C     ---COMPUTE FLOW RATES TO AND FROM CONSTANT HEAD BOUNDARIES---   CHK 480
      II=II+1                                                         CHK 490
      FLOW(II)=0.                                                     CHK 500
      JFLO(II,1)=K                                                    CHK 510
      JFLO(II,2)=I                                                    CHK 520
      JFLO(II,3)=J                                                    CHK 530
      IF (S(I,J-1,K).LT.0..OR.T(I,J-1,K).EQ.0.) GO TO 30              CHK 540
      X=(PHI(I,J,K)-PHI(I,J-1,K))*TR(I,J-1,K)*DELY(I)                 CHK 550
      IF(IEQN.EQ.ICHK(11)) X=X*DELZ(K)                                CHK 555
      FLOW(II)=FLOW(II)+X                                             CHK 560
      IF (X) 10,30,20                                                 CHK 570
   10 CHD1=CHD1+X                                                     CHK 580
      GO TO 30                                                        CHK 590
   20 CHD2=CHD2+X                                                     CHK 600
   30 IF (S(I,J+1,K).LT.0..OR.T(I,J+1,K).EQ.0.) GO TO 60              CHK 610
      X=(PHI(I,J,K)-PHI(I,J+1,K))*DELY(I)*TR(I,J,K)                   CHK 620
      IF(IEQN.EQ.ICHK(11)) X=X*DELZ(K)                                CHK 625
      FLOW(II)=FLOW(II)+X                                             CHK 630
      IF (X) 40,60,50                                                 CHK 640
   40 CHD1=CHD1+X                                                     CHK 650
      GO TO 60                                                        CHK 660
   50 CHD2=CHD2+X                                                     CHK 670
   60 IF (K.EQ.1) GO TO 90                                            CHK 680
      IF (S(I,J,K-1).LT.0..OR.T(I,J,K-1).EQ.0.) GO TO 90              CHK 690
      X=(PHI(I,J,K)-PHI(I,J,K-1))*TK(I,J,K-1)*AREA                    CHK 700
      FLOW(II)=FLOW(II)+X                                             CHK 720
      IF (X) 70,90,80                                                 CHK 730
   70 CHD1=CHD1+X                                                     CHK 740
      GO TO 90                                                        CHK 750
   80 CHD2=CHD2+X                                                     CHK 760
   90 IF (K.EQ.K0) GO TO 120                                          CHK 770
      IF (S(I,J,K+1).LT.0..OR.T(I,J,K+1).EQ.0.) GO TO 120             CHK 780
      X=(PHI(I,J,K)-PHI(I,J,K+1))*TK(I,J,K)*AREA                      CHK 790
      FLOW(II)=FLOW(II)+X                                             CHK 800
      IF (X) 100,120,110                                              CHK 810
  100 CHD1=CHD1+X                                                     CHK 820
      GO TO 120                                                       CHK 830
  110 CHD2=CHD2+X                                                     CHK 840
  120 IF (S(I-1,J,K).LT.0..OR.T(I-1,J,K).EQ.0.) GO TO 150             CHK 850
      X=(PHI(I,J,K)-PHI(I-1,J,K))*TC(I-1,J,K)*DELX(J)                 CHK 860
      IF(IEQN.EQ.ICHK(11)) X=X*DELZ(K)                                CHK 865
      FLOW(II)=FLOW(II)+X                                             CHK 870
      IF (X) 130,150,140                                              CHK 880
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  130 CHD1=CHD1+X                                                         CHK 890
      GO TO 150                                                           CHK 900
  140 CHD2=CHD2+X                                                         CHK 910
  150 IF (S(I+1,J,K).LT.0..OR.T(I+1,J,K).EQ.0.) GO TO 220                 CHK 920
      X=(PHI(I,J,K)-PHI(I+1,J,K))*TC(I,J,K)*DELX(J)                       CHK 930
      IF(IEQN.EQ.ICHK(11)) X=X*DELZ(K)                                    CHK 935
      FLOW(II)=FLOW(II)+X                                                 CHK 940
      IF (X) 160,220,170                                                  CHK 950
  160 CHD1=CHD1+X                                                         CHK 960
      GO TO 220                                                           CHK 970
  170 CHD2=CHD2+X                                                         CHK 980
      GO TO 220                                                           CHK 990
C                                                                         CHK1000
C       ---CHECK FOR EQUATION BEING SOLVED---                             CHK1001
  180 IF(IEQN.EQ.ICHK(11)) GO TO 211                                      CHK1002
C                                                                         CHK1003
C     ---EQUATION 4---                                                    CHK1004
C     ---RECHARGE AND WELLS---                                            CHK1010
      IF (K.EQ.KO.AND.IQRE.EQ.ICHK(7)) QREFLX=QREFLX+QRE(I,J)*AREA        CHK1020
      IF (WELL(I,J,K)) 190,210,200                                        CHK1030
  190 PUMP=PUMP+WELL(I,J,K)*AREA                                          CHK1040
      GO TO 210                                                           CHK1050
  200 CFLUX=CFLUX+WELL(I,J,K)*AREA                                        CHK1060
C                                                                         CHK1070
C     ---COMPUTE VOLUME FROM STORAGE---                                   CHK1080
  210 STOR=STOR+S(I,J,K)*(OLD(I,J,K)-PHI(I,J,K))*AREA                     CHK1090
C                                                                           ***
C     HEAD DEPENDENT STREAM OPTION.                                         ***
C                                                                           ***
      HDD=PHI(I,J,K)                                                        ***
      IF(HDD.LT.HB(I,J,K)) HDD=HB(I,J,K)                                    ***
      IF(HDD.GE.RHSS(I,J,K)) XRNET=(RHSS(I,J,K)-HDD)*RCG(I,J,K)*AREA        ***
      IF(HDD.LT.RHSS(I,J,K)) XRNET=(RHSS(I,J,K)-HDD)*RCL(I,J,K)*AREA        ***
      IF(K.EQ.2) STRLK(I,J)=XRNET                                           ***
      FLUXS=FLUXS+XRNET                                                     ***
      IF(XRNET.LT.0.) RFLOUT=RFLOUT-XRNET                                   ***
      IF(XRNET.GT.0.) RFLIN=RFLIN+XRNET                                     ***
C                                                                           ***
C     STREAM/AQUIFER FLOW OUTPUT BY ZONE.                                   ***
C                                                                           ***
      IF(XRNET.EQ.0.) GO TO 219                                             ***
      IF(XRNET.LT.0.) GO TO 217                                             ***
      DO 215 NNN=1,NZNS                                                     ***
      IF(IZN(I,J).EQ.NNN) ZINSUM(NNN)=ZINSUM(NNN)+XRNET                     ***
  215 IF(IZN(I,J).EQ.NNN) GO TO 219                                         ***
  217 DO 218 NNN=1,NZNS                                                     ***
      IF(IZN(I,J).EQ.NNN) ZOUTSM(NNN)=ZOUTSM(NNN)-XRNET                     ***
  218 IF(IZN(I,J).EQ.NNN) GO TO 219                                         ***
C                                                                           ***
C     HEAD DEPENDENT STREAM OPTION.                                         ***
C                                                                           ***
  219 IF(XRNET.LT.0.) FLXN=FLXN-XRNET                                       ***
      IF(KKK.NE.NUMT.AND.KKKK.NE.0) GO TO 220                               ***
```

```
      IF(XRNET.EQ.0.) GO TO 220                                          ***
      IF(ISBOUT.NE.1) GO TO 220                                          ***
      MMM=MMM+1                                                          ***
      IF((MOD(MMM,2)).NE.0) WRITE(6,310) I,J,K,XRNET                     ***
      IF((MOD(MMM,2)).EQ.0) WRITE(6,311) I,J,K,XRNET                     ***
C                                                                        ***
C     OPTION TO WRITE ON FILE STREAM/AQUIFER FLOW                        ***
C     IN WELL CARD FORMAT.                                               ***
C                                                                        ***
      IF(IWLWD.NE.1) GO TO 220                                           ***
      IF(XRNET.LT.0.) WRITE(15,2060)K,I,J,XRNET                          ***
      GO TO 220                                                       CHK1091
C                                                                     CHK1092
C     ---EQUATION 3---                                                CHK1093
C     ---RECHARGE AND WELLS---                                        CHK1094
  211 IF (K.EQ.KO.AND.IQRE.EQ.ICHK(7)) QREFLX=QREFLX+QRE(I,J)*VOLUME  CHK1095
      IF (WELL(I,J,K)) 212,214,213                                    CHK1096
  212 PUMP=PUMP+WELL(I,J,K)*VOLUME                                    CHK1097
      GO TO 214                                                       CHK1098
  213 CFLUX=CFLUX+WELL(I,J,K)*VOLUME                                  CHK1099
C                                                                     CHK1100
C     ---COMPUTE VOLUME FROM STORAGE---                               CHK1101
  214 STOR=STOR+S(I,J,K)*(OLD(I,J,K)-PHI(I,J,K))*VOLUME               CHK1102
C                                                                        ***
C     HEAD DEPENDENT STREAM OPTION.                                      ***
C                                                                        ***
      HDD=PHI(I,J,K)                                                     ***
      IF(HDD.LT.HB(I,J,K)) HDD=HB(I,J,K)                                 ***
      XRNET=(RHSS(I,J,K)-HDD)*RCG(I,J,K)*VOLUME                          ***
      FLUXS=FLUXS+XRNET                                                  ***
      IF(XRNET.LT.0.) RFLOUT=RFLOUT-XRNET                                ***
      IF(XRNET.GT.0.) RFLIN=RFLIN+XRNET                                  ***
      IF(XRNET.LT.0.) FLXN=FLXN-XRNET                                    ***
      IF(KKK.NE.NUMT.AND.KKKK.NE.0) GO TO 220                            ***
      IF(XRNET.EQ.0.) GO TO 220                                          ***
      WRITE(6,310) I,J,K,XRNET                                           ***
  220 CONTINUE                                                        CHK1103
C     .................................................................CHK1110
      IF(IR.NE.1) GO TO 225                                              ***
      IF(KKK.NE.NUMT.AND.KKKK.NE.0) GO TO 225                            ***
C                                                                        ***
C     STREAM/AQUIFER FLOW OUTPUT BY ZONE.                                ***
C                                                                        ***
      WRITE(6,315)                                                       ***
      WRITE(6,316)                                                       ***
      DO 222 LL=1,NZNS                                                   ***
  222 WRITE(6,317) LL,ZINSUM(LL),ZOUTSM(LL)                              ***
C                                                                        ***
C     HEAD DEPENDENT STREAM OPTION.                                      ***
C                                                                        ***
      WRITE(6,320)                                                       ***
      WRITE(6,325)                                                       ***
      WRITE(6,330) RFLIN,RFLOUT                                          ***
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C                                                                       CHK1120
C     ---COMPUTE CUMULATIVE VOLUMES, TOTALS, AND DIFFERENCES---         CHK1130
C                                                                         ***
C     WRITE STREAM/AQUIFER FLOW ON FILE                                   ***
C     FOR EACH GRID BLOCK.                                                ***
C                                                                         ***
      IF(ISLEAK.NE.1) GO TO 225                                           ***
      DO 224 I=1,IO                                                       ***
  224 WRITE(12,2040) (STRLK(I,J), J=1,JO)                                 ***
C                                                                         ***
C     OPTION TO WRITE SELECTED DATA FOR FINAL TIME STEP                   ***
C     ON FILE FOR ALL PUMPING PERIODS IN A TRANSIENT RUN.                 ***
C                                                                         ***
  225 IF(IPPOUT.NE.1) GO TO 9                                             ***
      IF(KT.NE.NUMT) GO TO 9                                              ***
      DO 19 I=1,IO                                                        ***
      DO 19 J=1,JO                                                        ***
      IF(IZN(I,J).EQ.0) GO TO 19                                          ***
      DRAW2=STRT(I,J,2)-PHI(I,J,2)                                        ***
      WRITE(15,2070) KP,I,J,IZN(I,J),PHI(I,J,2),DRAW2,STRLK(I,J)          ***
   19 CONTINUE                                                            ***
    9 FLXPT=0.                                                            ***
      STORT=STORT+STOR                                                  CHK1150
      STOR=STOR/DELT                                                    CHK1160
      FLUXT=FLUXT+FLUXS*DELT                                              ***
      FLXNT=FLXNT+FLXN*DELT                                               ***
      FLXPT=FLUXT+FLXNT                                                   ***
      QRET=QRET+QREFLX*DELT                                             CHK1170
      CHDT=CHDT-CHD1*DELT                                               CHK1180
      CHST=CHST+CHD2*DELT                                               CHK1190
      PUMPT=PUMPT-PUMP*DELT                                             CHK1200
      CFLUXT=CFLUXT+CFLUX*DELT                                          CHK1210
      TOTL1=STORT+QRET+CFLUXT+CHST+FLXPT                                CHK1220
      TOTL2=CHDT+PUMPT+ETFLXT+FLXNT                                     CHK1230
      SUMR=QREFLX+CFLUX+CHD2+CHD1+PUMP+ETFLUX+FLUXS+STOR                CHK1240
      DIFF=TOTL2-TOTL1                                                  CHK1250
      PERCNT=0.0                                                        CHK1260
C                                                                         ***
C     OPTION TO COMPUTE STATISTICS ON ZONE RESIDUALS.                     ***
C                                                                         ***
      IF(ISTAT.EQ.0) GO TO 241                                            ***
      DO 232 I=1,KO                                                       ***
      DO 232 J=1,NZNS                                                     ***
      RESID(I,J)=0.                                                       ***
      ARESID(I,J)=0.                                                      ***
      NCOUNT(I,J)=0                                                       ***
      XMAX(I,J)=0.                                                        ***
      XMIN(I,J)=0.                                                        ***
  232 RESID2(I,J)=0.                                                      ***
      DO 238 K=1,KO                                                       ***
      DO 236 I=2,I1                                                       ***
      DO 236 J=2,J1                                                       ***
      IF(IZN(I,J).EQ.0) GO TO 236                                         ***
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      DO 234 NNN=1,NZNS                                                 ***
      IF(IZN(I,J).EQ.NNN) GO TO 233                                     ***
      GO TO 234                                                         ***
  233 RESID(K,NNN)=RESID(K,NNN)+(STRT(I,J,K)-PHI(I,J,K))                ***
      WW=STRT(I,J,K)-PHI(I,J,K)                                         ***
      ARESID(K,NNN)=ARESID(K,NNN)+ABS(WW)                               ***
      NCOUNT(K,NNN)=NCOUNT(K,NNN)+1                                     ***
      XMAX(K,NNN)=AMAX1(XMAX(K,NNN),WW)                                 ***
      XMIN(K,NNN)=AMIN1(XMIN(K,NNN),WW)                                 ***
      RESID2(K,NNN)=RESID2(K,NNN)+(STRT(I,J,K)-PHI(I,J,K))**2           ***
      GO TO 236                                                         ***
  234 CONTINUE                                                          ***
  236 CONTINUE                                                          ***
  238 CONTINUE                                                          ***
      WRITE(6,332)                                                      ***
      WRITE(6,334)                                                      ***
      DO 239 K=1,K0                                                     ***
      DO 239 NNN=1,NZNS                                                 ***
      XMEAN=RESID(K,NNN)/NCOUNT(K,NNN)                                  ***
      AMEAN=ARESID(K,NNN)/NCOUNT(K,NNN)                                 ***
      SDMEAN=SQRT((NCOUNT(K,NNN)*RESID2(K,NNN)-RESID(K,NNN)**2)/(NCOUNT( ***
     1K,NNN)*(NCOUNT(K,NNN)-1)))                                        ***
  239 WRITE(6,336) K,NNN,NCOUNT(K,NNN),XMEAN,AMEAN,SDMEAN,XMAX(K,NNN),XM ***
     1IN(K,NNN)                                                         ***
  241 IF(TOTL2.EQ.0.) GO TO 230                                         ***
      PERCNT=DIFF/TOTL2*100.                                            CHK1280
  230 RETURN                                                            CHK1290
C     ..................................................................CHK1300
C                                                                       CHK1310
C     ---PRINT RESULTS---                                               CHK1320
C     ************************                                          CHK1330
      ENTRY CWRITE                                                      CHK1340
C     ************************                                          CHK1350
C                                                                       CHK1360
      WRITE (6,260) STOR,QREFLX,STORT,CFLUX,QRET,PUMP,CFLUXT,ETFLUX,CHSTCHK1370
     1,FLXPT,CHD2,TOTL1,CHD1,FLUX,FLUXS,ETFLXT,CHDT,SUMR,PUMPT,FLXNT,TOTCHK1380
     2L2,DIFF,PERCNT                                                    CHK1390
      IF (NCH.EQ.0) GO TO 240                                           CHK1400
      WRITE (6,270)                                                     CHK1410
      WRITE (6,280) ((JFLO(I,J),J=1,3),FLOW(I),I=1,NCH)                 CHK1420
C                                                                       CHK1430
C     ---COMPUTE VERTICAL FLOW---                                       CHK1440
  240 X=0.                                                              CHK1450
      Y=0.                                                              CHK1460
      IF (K0.EQ.1) RETURN                                               CHK1470
      DO 250 I=2,I1                                                     CHK1480
      DO 250 J=2,J1                                                     CHK1490
      X=X+(PHI(I,J,1)-PHI(I,J,2))*TK(I,J,1)*DELX(J)*DELY(I)             CHK1500
  250 Y=Y+(PHI(I,J,K1)-PHI(I,J,K0))*TK(I,J,K1)*DELX(J)*DELY(I)          CHK1520
      WRITE (6,290) Y,X                                                 CHK1540
C                                                                       ***
C     COMPUTE VERTICAL FLOW TOTALS BETWEEN LAYERS FOR EACH ZONE.        ***
C                                                                       ***
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      DO 394 I=1,NZNS                                                    ***
      VFUP(I)=0.                                                         ***
  394 VFDOWN(I)=0.                                                       ***
      DO 400 I=2,I1                                                      ***
      DO 400 J=2,J1                                                      ***
      IF(IZN(I,J).EQ.0) GO TO 400                                        ***
      DO 398 NNN=1,NZNS                                                  ***
      IF(IZN(I,J).EQ.NNN) GO TO 396                                      ***
      GO TO 398                                                          ***
  396 XYZ=PHI(I,J,2)-PHI(I,J,1)                                          ***
      IF(XYZ.GE.0.) VFDOWN(NNN)=VFDOWN(NNN)+XYZ*TK(I,J,1)*DELX(J)*DELY(I ***
     1)                                                                  ***
      IF(XYZ.LT.0.) VFUP(NNN)=VFUP(NNN)-XYZ*TK(I,J,1)*DELX(J)*DELY(I)    ***
      GO TO 400                                                          ***
  398 CONTINUE                                                           ***
  400 CONTINUE                                                           ***
      WRITE(6,386)                                                       ***
      WRITE(6,387)                                                       ***
      DO 390 I=1,NZNS                                                    ***
  390 WRITE(6,388) I,VFDOWN(I),VFUP(I)                                   ***
C                                                                        ***
C     OPTION TO COMPUTE ZONE TO ZONE LATERAL FLOW TOTALS.                ***
C                                                                        ***
      IF(IZTOZ.NE.1) GO TO 560                                           ***
      DO 550 K=1,KO                                                      ***
      WRITE(6,1000) K                                                    ***
      DO 540 IMM=1,NZNS                                                  ***
      DO 530 JMM=1,NZNS                                                  ***
      IF(IMM.EQ.JMM) GO TO 530                                           ***
      QQPOS=0.                                                           ***
      QQNEG=0.                                                           ***
      KPOS=0                                                             ***
      KNEG=0                                                             ***
      DO 510 I=2,I1                                                      ***
      DO 510 J=2,J1                                                      ***
      IF(IZN(I,J).NE.IMM) GO TO 510                                      ***
      IF(IZN(I+1,J).NE.JMM) GO TO 500                                    ***
      QQ=TC(I,J,K)*(PHI(I,J,K)-PHI(I+1,J,K))*DELX(J)                     ***
      IF(QQ.GE.0.) QQPOS=QQPOS+QQ                                        ***
      IF(QQ.GE.0.) KPOS=KPOS+1                                           ***
      IF(QQ.LT.0.) QQNEG=QQNEG-QQ                                        ***
      IF(QQ.LT.0.) KNEG=KNEG+1                                           ***
  500 IF(IZN(I,J+1).NE.JMM) GO TO 510                                    ***
      QQ=TR(I,J,K)*(PHI(I,J,K)-PHI(I,J+1,K))*DELY(I)                     ***
      IF(QQ.GE.0.) QQPOS=QQPOS+QQ                                        ***
      IF(QQ.GE.0.) KPOS=KPOS+1                                           ***
      IF(QQ.LT.0.) QQNEG=QQNEG-QQ                                        ***
      IF(QQ.LT.0.) KNEG=KNEG+1                                           ***
  510 CONTINUE                                                           ***
      IF(QQPOS.EQ.0.) GO TO 520                                          ***
      IF(KPOS.EQ.0) GO TO 520                                            ***
      YPOSAV=QQPOS/KPOS                                                  ***
      WRITE(6,1100) QQPOS,IMM,JMM,KPOS,YPOSAV                            ***
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  520 IF(QQNEG.EQ.0.) GO TO 530                                        ***
      IF(KNEG.EQ.0) GO TO 530                                          ***
      YNEGAV=QQNEG/KNEG                                                ***
      WRITE(6,1100) QQNEG,JMM,IMM,KNEG,YNEGAV                          ***
  530 CONTINUE                                                         ***
  540 CONTINUE                                                         ***
  550 CONTINUE                                                         ***
C                                                                      ***
C     OPTION TO COMPUTE MASS BALANCE FOR EACH ZONE.                    ***
C                                                                      ***
  560 IF(ITABLE.NE.1) RETURN                                           ***
C                                                                      ***
C     CONSTANT HEAD.                                                   ***
C                                                                      ***
      DO 1200 I=1,2                                                    ***
      DO 1200 J=1,NZNS                                                 ***
      RESID(I,J)=0.                                                    ***
 1200 ARESID(I,J)=0.                                                   ***
      DO 1360 NNNN=1,NZNS                                              ***
      XNGSUM=0.                                                        ***
      POSSUM=0.                                                        ***
      XNSUM=0.                                                         ***
      PSUM=0.                                                          ***
      DO 1350 I=2,I1                                                   ***
      DO 1350 J=2,J1                                                   ***
      IF(IZN(I,J).NE.NNNN) GO TO 1350                                  ***
      IF(S(I,J,2).LT.0.) GO TO 1320                                    ***
      IF(S(I+1,J,2).GE.0..OR.T(I+1,J,2).EQ.0.) GO TO 1230              ***
      X=(PHI(I,J,2)-PHI(I+1,J,2))*TC(I,J,2)*DELX(J)                    ***
      IF(X) 1210,1230,1220                                             ***
 1210 XNGSUM=XNGSUM-X                                                  ***
      GO TO 1230                                                       ***
 1220 POSSUM=POSSUM+X                                                  ***
 1230 IF(S(I-1,J,2).GE.0..OR.T(I-1,J,2).EQ.0.) GO TO 1260              ***
      X=(PHI(I,J,2)-PHI(I-1,J,2))*TC(I-1,J,2)*DELX(J)                  ***
      IF(X) 1240,1260,1250                                             ***
 1240 XNGSUM=XNGSUM-X                                                  ***
      GO TO 1260                                                       ***
 1250 POSSUM=POSSUM+X                                                  ***
 1260 IF(S(I,J+1,2).GE.0..OR.T(I,J+1,2).EQ.0.) GO TO 1290              ***
      X=(PHI(I,J,2)-PHI(I,J+1,2))*TR(I,J,2)*DELY(I)                    ***
      IF(X) 1270,1290,1280                                             ***
 1270 XNGSUM=XNGSUM-X                                                  ***
      GO TO 1290                                                       ***
 1280 POSSUM=POSSUM+X                                                  ***
 1290 IF(S(I,J-1,2).GE.0..OR.T(I,J-1,2).EQ.0.) GO TO 1350              ***
      X=(PHI(I,J,2)-PHI(I,J-1,2))*TR(I,J-1,2)*DELY(I)                  ***
      IF(X) 1300,1350,1310                                             ***
 1300 XNGSUM=XNGSUM-X                                                  ***
      GO TO 1350                                                       ***
 1310 POSSUM=POSSUM+X                                                  ***
      GO TO 1350                                                       ***
 1320 X=(PHI(I,J,2)-PHI(I,J,1))*TK(I,J,1)*DELX(J)*DELY(I)              ***
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      IF(X) 1330,1350,1340                                                   ***
 1330 XNSUM=XNSUM-X                                                          ***
      GO TO 1350                                                             ***
 1340 PSUM=PSUM+X                                                            ***
 1350 CONTINUE                                                               ***
      RESID(1,NNNN)=POSSUM                                                   ***
      RESID(2,NNNN)=XNGSUM                                                   ***
      ARESID(1,NNNN)=PSUM                                                    ***
      ARESID(2,NNNN)=XNSUM                                                   ***
 1360 CONTINUE                                                               ***
C                                                                            ***
C     LATERAL FLOW.                                                          ***
C                                                                            ***
      DO 1370 I=1,2                                                          ***
      DO 1370 J=1,NZNS                                                       ***
      XMAX(I,J)=0.                                                           ***
 1370 XMIN(I,J)=0.                                                           ***
      DO 1510 K=1,KO                                                         ***
      DO 1500 NN=1,NZNS                                                      ***
      QQPOS=0.                                                               ***
      QQNEG=0.                                                               ***
      DO 1490 I=2,I1                                                         ***
      DO 1490 J=2,J1                                                         ***
      IF(IZN(I,J).NE.NN) GO TO 1490                                          ***
      IF(IZN(I,J).EQ.0) GO TO 1490                                           ***
      IF(S(I+1,J,K).LT.0..OR.T(I+1,J,K).EQ.0..OR.IZN(I+1,J).EQ.NN) GO TO     ***
     1 1400                                                                  ***
      X=TC(I,J,K)*(PHI(I,J,K)-PHI(I+1,J,K))*DELX(J)                          ***
      IF(X) 1380,1400,1390                                                   ***
 1380 QQNEG=QQNEG-X                                                          ***
      GO TO 1400                                                             ***
 1390 QQPOS=QQPOS+X                                                          ***
 1400 IF(S(I-1,J,K).LT.0..OR.T(I-1,J,K).EQ.0..OR.IZN(I-1,J).EQ.NN) GO TO     ***
     1 1430                                                                  ***
      X=TC(I-1,J,K)*(PHI(I,J,K)-PHI(I-1,J,K))*DELX(J)                        ***
      IF(X) 1410,1430,1420                                                   ***
 1410 QQNEG=QQNEG-X                                                          ***
      GO TO 1430                                                             ***
 1420 QQPOS=QQPOS+X                                                          ***
 1430 IF(S(I,J+1,K).LT.0..OR.T(I,J+1,K).EQ.0..OR.IZN(I,J+1).EQ.NN) GO TO     ***
     1 1460                                                                  ***
      X=TR(I,J,K)*(PHI(I,J,K)-PHI(I,J+1,K))*DELY(I)                          ***
      IF(X) 1440,1460,1450                                                   ***
 1440 QQNEG=QQNEG-X                                                          ***
      GO TO 1460                                                             ***
 1450 QQPOS=QQPOS+X                                                          ***
 1460 IF(S(I,J-1,K).LT.0..OR.T(I,J-1,K).EQ.0..OR.IZN(I,J-1).EQ.NN) GO TO     ***
     1 1490                                                                  ***
      X=TR(I,J-1,K)*(PHI(I,J,K)-PHI(I,J-1,K))*DELY(I)                        ***
      IF(X) 1470,1490,1480                                                   ***
 1470 QQNEG=QQNEG-X                                                          ***
      GO TO 1490                                                             ***
 1480 QQPOS=QQPOS+X                                                          ***
```

```
 1490 CONTINUE                                                          ***
      XMAX(K,NN)=QQPOS                                                  ***
      XMIN(K,NN)=QQNEG                                                  ***
 1500 CONTINUE                                                          ***
 1510 CONTINUE                                                          ***
C                                                                       ***
C     WELLS.                                                            ***
C                                                                       ***
      DO 1515 I=1,2                                                     ***
      DO 1515 J=1,NZNS                                                  ***
      BDYQ(I,J)=0.                                                      ***
 1515 RESID2(I,J)=0.                                                    ***
      DO 1560 K=1,KO                                                    ***
      DO 1550 NNN=1,NZNS                                                ***
      QNEG=0.                                                           ***
      QPOS=0.                                                           ***
      DO 1540 I=2,I1                                                    ***
      DO 1540 J=2,J1                                                    ***
      IF(IZN(I,J).NE.NNN) GO TO 1540                                    ***
      X=WELL(I,J,K)*DELX(J)*DELY(I)                                     ***
      IF(X) 1520,1540,1530                                              ***
 1520 QNEG=QNEG-X                                                       ***
      GO TO 1540                                                        ***
 1530 QPOS=QPOS+X                                                       ***
 1540 CONTINUE                                                          ***
      BDYQ(K,NNN)=QPOS                                                  ***
      RESID2(K,NNN)=QNEG                                                ***
 1550 CONTINUE                                                          ***
 1560 CONTINUE                                                          ***
C                                                                       ***
C     RECHARGE.                                                         ***
C                                                                       ***
      DO 1580 NN=1,NZNS                                                 ***
      RECHQ(NN)=0.                                                      ***
      DO 1570 I=2,I1                                                    ***
      DO 1570 J=2,J1                                                    ***
      IF(IZN(I,J).NE.NN) GO TO 1570                                     ***
      IF(S(I,J,2).LT.0.) GO TO 1570                                     ***
      RECHQ(NN)=RECHQ(NN)+QRE(I,J)*DELX(J)*DELY(I)                      ***
 1570 CONTINUE                                                          ***
 1580 CONTINUE                                                          ***
C                                                                       ***
C     STORAGE.                                                          ***
C                                                                       ***
      DO 1590 I=1,2                                                     ***
      DO 1590 J=1,NZNS                                                  ***
 1590 STORAG(I,J)=0.                                                    ***
      DO 1620 K=1,KO                                                    ***
      DO 1610 NNN=1,NZNS                                                ***
      DO 1600 I=2,I1                                                    ***
      DO 1600 J=2,J1                                                    ***
      IF(S(I,J,K).LT.0.) GO TO 1600                                     ***
      IF(DELT.LE.0.0) GO TO 1600                                        ***
```

```
      IF(IZN(I,J).NE.NNN) GO TO 1600                                    ***
      STORAG(K,NNN)=STORAG(K,NNN)+S(I,J,K)*(OLD(I,J,K)-PHI(I,J,K))*DELX( ***
     1J)*DELY(I)/DELT                                                   ***
 1600 CONTINUE                                                          ***
 1610 CONTINUE                                                          ***
 1620 CONTINUE                                                          ***
C                                                                       ***
C     TOTALS.                                                           ***
C                                                                       ***
      DO 1630 N=1,NZNS                                                  ***
      X1STOT(N)=STORAG(1,N)+ARESID(1,N)+XMIN(1,N)+BDYQ(1,N)             ***
      X2STOT(N)=STORAG(2,N)+RECHQ(N)+ZINSUM(N)+RESID(2,N)+XMIN(2,N)+BDYQ ***
     1(2,N)                                                             ***
      X1DTOT(N)=RESID2(1,N)+ARESID(2,N)+XMAX(1,N)                       ***
      X2DTOT(N)=RESID2(2,N)+ZOUTSM(N)+RESID(1,N)+XMAX(2,N)              ***
      SDDIFF(N)=(X1STOT(N)+X2STOT(N))-(X1DTOT(N)+X2DTOT(N))             ***
      IF(X1STOT(N).NE.0.0.OR.X2STOT(N).NE.0.0) GO TO 1625               ***
      IF(X1DTOT(N).EQ.0.0.AND.X2DTOT(N).EQ.0.0) GO TO 1630              ***
 1625 PCDIFF(N)=2.*SDDIFF(N)*100./(X1STOT(N)+X2STOT(N)+X1DTOT(N)+X2DTOT( ***
     1N))                                                               ***
 1630 CONTINUE                                                          ***
      DO 1640 N=1,NZNS                                                  ***
      WRITE(6,1700) N                                                   ***
      WRITE(6,1710)                                                     ***
      WRITE(6,1720)                                                     ***
      WRITE(6,1730)                                                     ***
      WRITE(6,1740)                                                     ***
      WRITE(6,1760)                                                     ***
      WRITE(6,1770)                                                     ***
      WRITE(6,1780)                                                     ***
      WRITE(6,1790)                                                     ***
      WRITE(6,1800) STORAG(1,N),STORAG(2,N)                             ***
      WRITE(6,1810) RECHQ(N)                                            ***
      WRITE(6,1820) ZINSUM(N)                                           ***
      WRITE(6,1830) ARESID(1,N),RESID(2,N)                              ***
      WRITE(6,1840) XMIN(1,N),XMIN(2,N)                                 ***
      WRITE(6,1850) BDYQ(1,N),BDYQ(2,N)                                 ***
      WRITE(6,1860)                                                     ***
      WRITE(6,1870) X1STOT(N),X2STOT(N)                                 ***
      WRITE(6,1880)                                                     ***
      WRITE(6,1890)                                                     ***
      WRITE(6,1900) RESID2(1,N),RESID2(2,N)                             ***
      WRITE(6,1910) ZOUTSM(N)                                           ***
      WRITE(6,1920) ARESID(2,N),RESID(1,N)                              ***
      WRITE(6,1930) XMAX(1,N),XMAX(2,N)                                 ***
      WRITE(6,1940)                                                     ***
      WRITE(6,1950) X1DTOT(N),X2DTOT(N)                                 ***
      WRITE(6,1960)                                                     ***
      WRITE(6,1970)                                                     ***
      WRITE(6,1980) SDDIFF(N)                                           ***
      WRITE(6,1990) PCDIFF(N)                                           ***
      WRITE(6,2000)                                                     ***
      WRITE(6,2010)                                                     ***
```

```
      WRITE(6,2020) VFUP(N)                                             ***
      WRITE(6,2030) VFDOWN(N)                                           ***
 1640 CONTINUE                                                          ***
      RETURN                                                            CHK1550
C                                                                       CHK1560
C     ---FORMATS---                                                     CHK1570
C                                                                       CHK1580
C     ------------------------------------------------------------------CHK1590
C                                                                       CHK1600
C                                                                       CHK1610
C                                                                       CHK1620
  260 FORMAT ('0',10X,'CUMULATIVE MASS BALANCE:',16X,'L**3',23X,'RATES FCHK1630
     1OR THIS TIME STEP:',16X,'L**3/T'/11X,24('-'),43X,25('-')//20X,'SOUCHK1640
     2RCES:',69X,'STORAGE =',F20.4/20X,8('-'),68X,'RECHARGE =',F20.4/27XCHK1650
     3,'STORAGE =',F20.2,35X,'CONSTANT FLUX =',F20.4/26X,'RECHARGE =',F2CHK1660
     40.2,41X,'PUMPING =',F20.4/21X,'CONSTANT FLUX =',F20.2,30X,'EVAPOTRCHK1670
     5ANSPIRATION =',F20.4/21X,'CONSTANT HEAD =',F20.2,34X,'CONSTANT HEACHK1680
     6D:'/27X,'LEAKAGE =',F20.2,46X,'IN =',F20.4/21X,'TOTAL SOURCES =',FCHK1690
     720.2,45X,'OUT =',F20.4/96X,'LEAKAGE:'/20X,'DISCHARGES:',45X,'FROM CHK1700
     8PREVIOUS PUMPING PERIOD =',F20.4/20X,11('-'),68X,'TOTAL =',F20.4/1CHK1710
     96X,'EVAPOTRANSPIRATION =',F20.2/21X,'CONSTANT HEAD =',F20.2,36X,'SCHK1720
     $UM OF RATES =',F20.4/19X'QUANTITY PUMPED =',F20.2/27X,'LEAKAGE =',CHK1730
     $F20.2/19X,'TOTAL DISCHARGE =',F20.2//17X,'DISCHARGE-SOURCES =',F20CHK1740
     $.2/15X,'PER CENT DIFFERENCE =',F20.2//)                           CHK1750
  270 FORMAT ('OFLOW RATES TO CONSTANT HEAD NODES:'/' ',34('-')//' ',3(9CHK1760
     1X,'K',4X,'I',4X,'J',5X,'RATE (L**3/T)')/' ',3(9X,'-',4X,'-',4X,'-'CHK1770
     2,5X,13('-'))/)                                                    CHK1780
  280 FORMAT (/(1X,3(I10,2I5,G18.7)))                                   CHK1790
  290 FORMAT ('OFLOW TO TOP LAYER =',G15.7,'   FLOW TO BOTTOM LAYER =',GCHK1800
     115.7,'       POSITIVE UPWARD')                                    CHK1810
  300 FORMAT('1',2X,                    'RATE IN CFS OF STREAM FLOW IN EACH BLO  ***
     1CK FOR THIS STEP ( OUT OF AQUIFER (-) )')                         ***
  305 FORMAT('0',5X,'I',5X,'J',5X,'K',8X,'STREAM',8X,25X,'I',           ***
     15X,'J',5X,'K',8X,'STREAM')                                        ***
  310 FORMAT(' ',4X,I2,4X,I2,5X,I1,6X,E10.4)                            ***
  311 FORMAT('+',72X,I2,4X,I2,5X,I1,6X,E10.4)                           ***
  315 FORMAT('1',2X,'TOTAL RATES,IN CFS,OF STREAM - AQUIFER FLOW BY ZONE ***
     1')                                                                ***
  316 FORMAT('0',12X,'ZONE',5X,'STREAMS INTO AQUIFER',5X,'AQUIFER INTO S ***
     1TREAMS')                                                          ***
  317 FORMAT('0',13X,I2,12X,E10.3,16X,E10.3)                            ***
  320 FORMAT('0',2X,                    'TOTAL RATE,IN CFS,OF STREAM FLOW IN MO ***
     1DEL AREA FOR THIS STEP')                                          ***
  325 FORMAT('0',5X,'STREAMS INTO AQUIFER',5X,'AQUIFER INTO STREAMS')   ***
  330 FORMAT(' ',10X,E10.4,15X,E10.4)                                   ***
  332 FORMAT('1',2X,'BASIC STATISTICS RELATING TO RESIDUALS AT ALL BLOCK ***
     1S')                                                               ***
  334 FORMAT('0',2X,'LAYER',2X,'ZONE',2X,'BLOCKS',4X,'MEAN',4X,'MEAN(ABS ***
     1)',2X,'ST.DEV.(MEAN)',2X,'MAX.DD',3X,'MAX.BU')                    ***
  336 FORMAT('0',4X,I1,5X,I2,4X,I4,5X,F5.1,5X,F5.1,8X,F5.1,7X,F6.1,4X,F6 ***
     1.1)                                                               ***
  386 FORMAT('1',4X,'TOTAL VERTICAL FLOW RATES BY ZONE (CFS)')          ***
  387 FORMAT('0',14X,'ZONE',8X,'DOWN',10X,'UP')                         ***
```

```
 388 FORMAT('0',15X,I2,5X,E10.3,3X,E10.3)                                ***
1000 FORMAT('1',10X,'FLOW BETWEEN ZONES IN LAYER',3X,I2)                  ***
1100 FORMAT('0',6X,F10.2,2X,'CFS FROM ZONE',2X,I2,2X,'INTO ZONE',2X,I2,   ***
    12X,'OVER',2X,I3,2X,'BLOCK BOUNDARIES (',2X,F10.2,2X,'CFS PER BOUND  ***
    2ARY  )')                                                            ***
1700 FORMAT('1',12X,'ZONE',2X,I2)                                         ***
1710 FORMAT(' ',11X,'----------')                                         ***
1720 FORMAT('0',11X,'MASS BALANCE')                                       ***
1730 FORMAT(' ',13X,'(IN CFS)')                                           ***
1740 FORMAT(' ',10X,'--------------')                                     ***
1760 FORMAT('0',34X,'LAYER  1',5X,'LAYER  2')                             ***
1770 FORMAT(' ',33X,'----------',3X,'----------')                         ***
1780 FORMAT('0',9X,'SOURCES')                                             ***
1790 FORMAT(' ',8X,'---------')                                           ***
1800 FORMAT(' ',19X,'STORAGE    = ',F11.3,2X,F11.3)                       ***
1810 FORMAT('0',18X,'RECHARGE    = ',13X,     F11.3)                      ***
1820 FORMAT('0',19X,'STREAMS    = ',13X,F11.3)                            ***
1830 FORMAT('0',21X,'RIVER    = ',F11.3,2X,F11.3)                         ***
1840 FORMAT('0',17X,'UNDERFLOW    = ',F11.3,2X,F11.3)                     ***
1850 FORMAT('0',18X,'BOUNDARY    = ',F11.3,2X,F11.3)                      ***
1860 FORMAT(' ',16X,'------------------------------------------')         ***
1870 FORMAT(' ',21X,'TOTAL    = ',F11.3,2X,F11.3)                         ***
1880 FORMAT('0',9X,'DISCHARGES')                                          ***
1890 FORMAT(' ',8X,'------------')                                        ***
1900 FORMAT(' ',19X,'PUMPING    = ',F11.3,2X,F11.3)                       ***
1910 FORMAT('0',19X,'STREAMS    = ',13X,F11.3)                            ***
1920 FORMAT('0',21X,'RIVER    = ',F11.3,2X,F11.3)                         ***
1930 FORMAT('0',17X,'UNDERFLOW    = ',F11.3,2X,F11.3)                     ***
1940 FORMAT(' ',15X,'--------------------------------------------')       ***
1950 FORMAT(' ',21X,'TOTAL    = ',F11.3,2X,F11.3)                         ***
1960 FORMAT('0',9X,'BALANCE')                                             ***
1970 FORMAT(' ',8X,'---------')                                           ***
1980 FORMAT(' ',15X,'TOTAL SOURCES  -  TOTAL DISCHARGES    = ',F11.3)     ***
1990 FORMAT('0',31X,'PERCENT DIFFERENCE    = ',F11.3)                     ***
2000 FORMAT('0',9X,'VERTICAL FLOW')                                       ***
2010 FORMAT(' ',8X,'--------------')                                      ***
2020 FORMAT(' ',15X,'FROM LAYER 1 TO LAYER 2    = ',F11.3)                ***
2030 FORMAT('0',15X,'FROM LAYER 2 TO LAYER 1    = ',F11.3)                ***
2040 FORMAT(8E10.4)                                                       ***
2050 FORMAT(3I5,2F10.1)                                                   ***
2060 FORMAT(3I10,F10.2)                                                   ***
2070 FORMAT(4I4,2F7.2,E10.4)                                              ***
     END


      SUBROUTINE PRNTAI(PHI,STRT,T,S,WELL,DELX,DELY)
C     ------------------------------------------------------------------
C     PRINT MAPS OF DRAWDOWN AND HYDRAULIC HEAD
C     ------------------------------------------------------------------
C
C     SPECIFICATIONS:
      REAL *8PHI,Z,XLABEL,YLABEL,TITLE,XN1,MESUR
      REAL *4K
```

```
C
      DIMENSION PHI(I0,J0,K0), STRT(I0,J0,K0), S(I0,J0,K0), WELL(I0,J0,K
     10), DELX(J0), DELY(I0), T(I0,J0,K0)
C
      COMMON /INTEGR/ I0,J0,K0,I1,J1,K1,I,J,K,NPER,KTH,ITMAX,LENGTH,KP,N
     1WEL,NUMT,IFINAL,IT,KT,IHEAD,IDRAW,IFLO,IERR,I2,J2,K2,IMAX,ITMX1,NC
     2H,IDK1,IDK2,IWATER,IQRE,IP,JP,IQ,JQ,IK,JK,K5,IPU1,IPU2,ITK,IEQN,KK   ***
     3K,KKKK,IR,ISTAT,MLTCHK,ISBOUT,IJKMAP,IVHMAP,IZTOZ,ITABLE,            ***
     4LAYDDN,ISLEAK,IOCTAP,IWLWD,IPPOUT                                    ***
      COMMON /PR/ XLABEL(3),YLABEL(6),TITLE(6),XN1,MESUR,PRNT(122),BLANK
     1(60),DIGIT(122),VF1(6),VF2(6),VF3(7),XSCALE,DINCH,SYM(17),XN(100),
     2YN(13),NA(4),N1,N2,N3,YSCALE,FACT1,FACT2
      RETURN
C     ..................................................................
C
C     ---INITIALIZE VARIABLES FOR PLOT---
C     ********************
      ENTRY MAP
C     ********************
      YDIM=0.
      WIDTH=0.
      DO 10 J=2,J1
   10 WIDTH=WIDTH+DELX(J)
      DO 20 I=2,I1
   20 YDIM=YDIM+DELY(I)
   30 XSF=DINCH*XSCALE
      YSF=DINCH*YSCALE
      NYD=YDIM/YSF
      IF (NYD*YSF.LE.YDIM-DELY(I1)/2.) NYD=NYD+1
      IF (NYD.LE.12) GO TO 40
      DINCH=YDIM/(12.*YSCALE)
      WRITE (6,330) DINCH
      IF (YSCALE.LT.1.0) WRITE (6,340)
      GO TO 30
   40 NXD=WIDTH/XSF
      IF (NXD*XSF.LE.WIDTH-DELX(J1)/2.) NXD=NXD+1
      N4=NXD*N1+1
      N5=NXD+1
      N6=NYD+1
      N8=N2*NYD+1
      NA(1)=N4/2-1
      NA(2)=N4/2
      NA(3)=N4/2+3
      NC=(N3-N8-10)/2
      ND=NC+N8
      NE=MAX0(N5,N6)
      VF1(3)=DIGIT(ND)
      VF2(3)=DIGIT(ND)
      VF3(3)=DIGIT(NC)
      XLABEL(3)=MESUR
      YLABEL(6)=MESUR
      DO 60 I=1,NE
      NNX=N5-I
```

```
      NNY=I-1
      IF (NNY.GE.N6) GO TO 50
      YN(I)=YSF*NNY/YSCALE
   50 IF (NNX.LT.0) GO TO 60
      XN(I)=XSF*NNX/YSCALE
   60 CONTINUE
      RETURN
C     ..................................................................
C
C     ********************
      ENTRY PRNTA(NG,LA)
C     ********************
C     ---VARIABLES INITIALIZED EACH TIME A PLOT IS REQUESTED---
      DIST=WIDTH-DELX(J1)/2.
      JJ=J1
      LL=1
      Z=NXD*XSF
      IF (NG.EQ.1) WRITE (6,300) (TITLE(I),I=1,3),LA
      IF (NG.EQ.2) WRITE (6,300) (TITLE(I),I=4,6),LA
      DO 290 I=1,N4
C
C     ---LOCATE X AXES---
      IF (I.EQ.1.OR.I.EQ.N4) GO TO 70
      PRNT(1)=SYM(12)
      PRNT(N8)=SYM(12)
      IF ((I-1)/N1*N1.NE.I-1) GO TO 90
      PRNT(1)=SYM(14)
      PRNT(N8)=SYM(14)
      GO TO 90
C
C     ---LOCATE Y AXES---
   70 DO 80 J=1,N8
      IF ((J-1)/N2*N2.EQ.J-1) PRNT(J)=SYM(14)
   80 IF ((J-1)/N2*N2.NE.J-1) PRNT(J)=SYM(13)
C
C     ---COMPUTE LOCATION OF NODES AND DETERMINE APPROPRIATE SYMBOL---
   90 IF (DIST.LT.0..OR.DIST.LT.Z-XN1*XSF) GO TO 240
      YLEN=DELY(2)/2.
      DO 220 L=2,I1
      J=YLEN*N2/YSF+1.5
      IF (T(L,JJ,LA).EQ.0.) GO TO 160
      IF (S(L,JJ,LA).LT.0.) GO TO 210
      INDX3=0
      GO TO (100,110), NG
  100 K=(STRT(L,JJ,LA)-PHI(L,JJ,LA))*FACT1
C     -TO CYCLE SYMBOLS FOR DRAWDOWN, REMOVE C FROM COL. 1 OF NEXT CARD-
C     K=AMOD(K,10.)
      GO TO 120
  110 K=PHI(L,JJ,LA)*FACT2
  120 IF (K) 130,160,140
  130 IF (J-2.GT.0) PRNT(J-2)=SYM(13)
      N=-K+.5
      IF (N.LT.100) GO TO 150
```

```
      GO TO 190
  140 N=K+.5
      IF (N.LT.100) GO TO 150
      IF (N.GT.999) GO TO 190
      INDX3=N/100
      IF (J-2.GT.0) PRNT(J-2)=SYM(INDX3)
      N=N-INDX3*100
  150 INDX1=MOD(N,10)
      IF (INDX1.EQ.0) INDX1=10
C     -TO CYCLE SYMBOLS FOR DRAWDOWN, REMOVE C FROM COL. 1 OF NEXT CARD-
C     IF (NG.EQ.1) GO TO 170
      INDX2=N/10
      IF (INDX2.GT.0) GO TO 180
      INDX2=10
      IF (INDX3.EQ.0) INDX2=15
      GO TO 180
  160 INDX1=15
  170 INDX2=15
  180 IF (J-1.GT.0) PRNT(J-1)=SYM(INDX2)
      PRNT(J)=SYM(INDX1)
      GO TO 220
  190 DO 200 II=1,3
      JI=J-3+II
  200 IF (JI.GT.0) PRNT(JI)=SYM(11)
  210 IF (S(L,JJ,LA).LT.0.) PRNT(J)=SYM(16)
  220 YLEN=YLEN+(DELY(L)+DELY(L+1))/2.
  230 DIST=DIST-(DELX(JJ)+DELX(JJ-1))/2.
      JJ=JJ-1
      IF (JJ.EQ.0) GO TO 240
      IF (DIST.GT.Z-XN1*XSF) GO TO 230
  240 CONTINUE
C
C     ---PRINT AXES,LABELS, AND SYMBOLS---
      IF (I-NA(LL).EQ.0) GO TO 260
      IF ((I-1)/N1*N1-(I-1)) 270,250,270
  250 WRITE (6,VF1) (BLANK(J),J=1,NC),(PRNT(J),J=1,N8),XN(1+(I-1)/6)
      GO TO 280
  260 WRITE (6,VF2) (BLANK(J),J=1,NC),(PRNT(J),J=1,N8),XLABEL(LL)
      LL=LL+1
      GO TO 280
  270 WRITE (6,VF2) (BLANK(J),J=1,NC),(PRNT(J),J=1,N8)
C
C     ---COMPUTE NEW VALUE FOR Z AND INITIALIZE PRNT---
  280 Z=Z-2.*XN1*XSF
      DO 290 J=1,N8
  290 PRNT(J)=SYM(15)
C
C     ---NUMBER AND LABEL Y AXIS AND PRINT LEGEND---
      WRITE (6,VF3) (BLANK(J),J=1,NC),(YN(I),I=1,N6)
      WRITE (6,320) (YLABEL(I),I=1,6)
      IF (NG.EQ.1) WRITE (6,310) FACT1
      IF (NG.EQ.2) WRITE (6,310) FACT2
      RETURN
```

```
C
C     ---FORMATS---
C
C     -----------------------------------------------------------------
C
C
  300 FORMAT ('1',49X,3A8,'LAYER',I4//)
  310 FORMAT ('0EXPLANATION'/' ',11('-')//' R = CONSTANT HEAD BOUNDARY'/
     1' *** = VALUE EXCEEDED 3 FIGURES'/' MULTIPLICATION FACTOR =',F8.3)
  320 FORMAT ('0',39X,6A8)
  330 FORMAT ('0',25X,10('*'),' TO FIT MAP WITHIN 12 INCHES, DINCH REVIS
     1ED TO',G15.7,1X,10('*'))
  340 FORMAT ('0',45X,'NOTE: GENERALLY SCALE SHOULD BE > OR = 1.0')
      END

      BLOCK DATA
C     ----------
C
C     SPECIFICATIONS:
      REAL *8XLABEL,YLABEL,TITLE,XN1,MESUR
C
      COMMON /SARRAY/ ICHK(13),LEVEL1(9),LEVEL2(9)
      COMMON /PR/ XLABEL(3),YLABEL(6),TITLE(6),XN1,MESUR,PRNT(122),BLANK
     1(60),DIGIT(122),VF1(6),VF2(6),VF3(7),XSCALE,DINCH,SYM(17),XN(100),
     2YN(13),NA(4),N1,N2,N3,YSCALE,FACT1,FACT2
C     *****************************************************************
C
      DATA ICHK/'DRAW','HEAD','MASS','DK1','DK2','WATE','RECH','PUN1','P
     1UN2','ITKR','EQN3',2*0/
      DATA SYM/'1','2','3','4','5','6','7','8','9','0','*','¢','-','+','
     1 ','R','W'/
      DATA PRNT/122*' '/,N1,N2,N3,XN1/6,10,133,.833333333D-1/,BLANK/60*'
     1 '/,NA(4)/1000/
      DATA XLABEL/' X DIS- ','TANCE IN',' MILES '/,YLABEL/'DISTANCE',' 
     1FROM OR','IGIN IN ','Y DIRECT','ION, IN ','MILES   '/,TITLE/'PLOT 
     2OF ','DRAWDOWN',' ','PLOT OF ','HYDRAULI','C HEAD'/
      DATA DIGIT/'1','2','3','4','5','6','7','8','9','10','11','12','13'
     1,'14','15','16','17','18','19','20','21','22','23','24','25','26',
     2'27','28','29','30','31','32','33','34','35','36','37','38','39','
     340','41','42','43','44','45','46','47','48','49','50','51','52','5
     43','54','55','56','57','58','59','60','61','62','63','64','65','66
     5','67','68','69','70','71','72','73','74','75','76','77','78',' 79
     6','80','81','82','83','84','85','86','87','88','89','90','91','92'
     7,'93','94','95','96','97','98','99','100','101','102','103',' 104'
     8,'105','106','107','108','109','110','111','112','113','114','115'
     9,'116','117','118','119','120','121','122'/
      DATA VF1/'(1H ',',',' ','A1,F','10.2',')'/
      DATA VF2/'(1H ',',',' ','A1,1','X,A8',')'/
      DATA VF3/'(1H0',',',' ','A1,F','3.1,','12F1','0.2)'/
C     *****************************************************************
      END
```

ATTACHMENT B

Instructions for use of model program

The following are the data input instructions for the model program used in this investigation. It is a modified version of the original instructions (Trescott (1975) and Trescott and Larson (1976)).

DATA INPUT INSTRUCTIONS

GROUND-WATER FLOW MODEL OF PART OF LANCASTER COUNTY
(Modified from original 3-D Model (Trescott, 1975)
by J.M. Gerhart and G.J. Lazorchick, 1980-1982)

Group I: Title, Simulation Options, and Problem Dimensions

This group of cards, which is read by the main program, contains data required to dimension the model. To specify an option on card 5, punch the characters underlined in the definition. For an option not used, that section of card 5 can be left blank.

Note: Default typing of variables applies for all data input.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
1	1-80	20A4	HEADING	Any title the user wishes to print on one line at the start of output.
2	1-52	13A4	HEADING	
3	1-10	I10	IO	Number of rows
	11-20	I10	JO	Number of columns
	21-30	I10	KO	Number of layers (specify as 1)
	31-40	I10	ITMAX	Maximum number of iterations per time step
	41-50	I10	NCH	Number of constant-head blocks
	51-60	I10	NZNS	Number of hydrogeologic units
	61-65	I5	IR	IR=1 if head-dependent stream output desired; blank otherwise
	66-70	I5	ISTAT	ISTAT=1 if residual statistics desired; blank otherwise
	71-75	I5	MLTCHK	MLTCHK=1 if spot check of hydraulic conductivity modification for topography desired; blank otherwise
4	1-5	I5	ISBOUT	ISBOUT=1 if block-by-block printout of stream-aquifer flow desired; blank otherwise
	6-10	I5	IJKMAP	IJKMAP=1 if maps of head change from STRT desired; blank otherwise

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
4	11-15	I5	IVHMAP	IVHMAP=1 if map of head difference between layers desired; blank otherwise
	16-20	I5	IZTOZ	IZTOZ=1 if printout of unit-to-unit flow desired; blank otherwise
	21-25	I5	ITABLE	ITABLE=1 if mass balance for each unit desired; blank otherwise
	26-30	I5	LAYDDN	LAYDDN=1 if head change from STRT in both layers to be written on file 11; blank otherwise
	31-35	I5	ISLEAK	ISLEAK=1 if stream-aquifer flow in each block to be written on file 12; blank otherwise
	36-40	I5	IOCTAP	IOCTAP=1 or 2 if head change between pumping periods 4 and 10 to be written on files 13 or14; blank otherwise
	41-45	I5	IWLWD	IWLWD=1 if rates of discharge in each stream block to be written on file 15 in format of well cards; blank otherwise
	46-50	I5	IPPOUT	IPPOUT=1 if head, head changes from STRT, and rates of stream discharge at end of each pumping period of transient simulation to be written on file 15; blank otherwise
5	1-4	A4	IDRAW	DRAW to print drawdown
	6-9	A4	IHEAD	HEAD to print hydraulic head
	11-14	A4	IFLOW	MASS to compute a mass balance
	16-18	A3	IDK1	DK1 to read initial head, elapsed time, and mass balance parameters from unit 4 on disk

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
5	21-23	A3	IDK2	DK2 to write computed head, elapsed time, and mass balance parameters on unit 4 (disk)
	26-29	A4	IWATER	WATE if the upper layer is unconfined
	31-34	A4	IQRE	RECH for a constant recharge that may be a function of space
	36-39	A4	IPU1	PUN1 to read initial head, elapsed time, and mass balance parameters from cards
	41-44	A4	IPU2	PUN2 to punch computed head, elapsed time, and mass balance parameters on cards

Group II: Scalar parameters

The parameters required in every problem are underlined. The other parameters are required as noted; when not required, their location on the card can be left blank. The G format is used to read E, F and I format data. Minimize mistakes by always right-justifying data in the field. If F format data do not contain significant figures to the right of the decimal point, the decimal point can be omitted.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
1	1-10	I10	NPER	Number of pumping periods for the simulation
	11-20	I10	KTH	Number of time steps between printouts

Note: To print only the results for the final time step in a pumping period, make KTH greater than the expected number of time steps. The program always prints the results for the final time step.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
	21-30	G10.0	ERR	Error criterion for closure (L)

Note: When the head change in all blocks on subsequent iterations is less than this value (for example, 0.01 foot), the program has converged to a solution for the time step.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
	31-40	I10	LENGTH	Number of iteration parameters (5 for SIP)

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
2	1-10	G10.0	XSCALE	Factor to convert model length unit to unit used in X direction on maps (e.g. to convert from feet to miles, XSCALE= 5280) For no maps, card 2 is blank
	11-20	G10.0	YSCALE	Factor to convert model length unit to unit used in Y direction on maps
	21-30	G10.0	DINCH	Number of map units per inch
	31-40	G10.0	FACT1	Factor to adjust value of drawdown printed*(1/FACT1= contourinterval)
	41-49	9I1	LEVEL1(I)	Layers for which drawdown maps are to be printed. List the layers starting in column 41; the first zero entry terminates the printing of drawdown maps (up to 9 layers)
	51-60	G10.0	FACT2	Factor to adjust value of head printed*
	61-69	9I1	LEVEL2(I)	Layers for which head maps are to be printed. List layers starting in column 61; the first zero entry terminates the printing of head maps.
	71-78	A8	MESUR	Name of map length unit

*Value of drawdown or head	FACT 1 or FACT 2	Printed value
	0.01	1
	0.1	5
52.57	1.0	53
	10.0	526
	100.0	***

Note: On the following three cards (3, 4, 5) are parameters in which elapsed time and cumulative volumes for mass balance are stored. For the start of a simulation insert three blank cards. For continuation of a previous run using cards as input, replace the three blank cards with the first three cards of punched output from the previous run. Using data from disk for input, leave the three blank cards in the data deck.

CARD	COLUMNS	FORMAT	VARIABLE
3	1-20	G20.10	SUM
	21-40	G20.10	SUMP
	41-60	G20.10	PUMPT
	61-80	G20.10	CFLUXT
4	1-20	G20.10	QRET
	21-40	G20.10	CHST
	41-60	G20.10	CHDT
	61-80	G20.10	FLUXT
5	1-20	G20.10	STORT
	21-40	G20.10	ETFLXT
	41-60	G20.10	FLXNT

Group III: Array Data

Each of the following data sets (except data sets 1, 11, 12, 13) consists of a parameter card and, if the data set contains variable data, a set of data cards. If the data set requires data for each layer, a parameter card and data cards (for layers with variable data) are required for each layer. Each parameter card contains at least five variables:

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
	1-10	G10.0	FAC	If IVAR=0, FAC is the value assigned to every element of the matrix for this layer. If IVAR=1, FAC is the multiplication for the following set of data cards for this layer.
	11-20	G10.0	IVAR	=0 if no data cards are to be read for this layer. =1 if data cards for this layer follow.
	21-30	G10.0	IPRN	=0 if input data for this layer are to be printed; =1 if input data for the layer are not to be printed.
	61-70	G10.0	IRECS	=0 if the matrix is being read from cards or if each element is being set equal to FAC. =1 if the matrix is to be read from disk (unit 2)
	71-80	G10.0	IRECD	=0 if the matrix is not to be stored on disk. =1 if the matrix being read from cards or set equal to FAC is to be stored on disk (unit 2) for later retrieval.

When data cards are included, start each row on a new card. To prepare a set of data cards for an array that is a function of space, the general procedure is to overlay the finite-difference grid on a contoured map of the parameter and record the average value of the parameter for each finite-difference block on coding forms according to the appropriate format. In general, record only significant digits and no decimal points (except for data set 2); use the multiplication factor to convert the data to their appropriate values. For example, if DELX ranges from 1000 to 15000 feet, coded values should range from 1-15; the multiplication factor (FAC) would be 1000.

DATA SET	COLUMNS	FORMAT	VARIABLE	DEFINITION
1	1-80	8F10.4	PHI(I,J,K)	Head values for continuation of a previous run(L)(for all layers)

Note: For a new simulation this data set is omitted. Do not include a parameter card with this data set.

DATA SET	COLUMNS	FORMAT	VARIABLE	DEFINITION
2	1-80	8F10.4	STRT(I,J,K)	Starting head matrix(L) (for all layers)
3	1-80	20F4.0	S(I,J,K)	Location of constant-head blocks (for all layers)

Note: This matrix is only used to locate constant-head blocks. Code a negative number at constant-head blocks. At these blocks, T must be greater than zero.

DATA SET	COLUMNS	FORMAT	VARIABLE	DEFINITION
4	1-80	40F2.0	PERM(I,J)	Topographic setting(1=hilltop to 5=valley bottom)(only once for all layers)
5	1-80	20F4.0	BOTTOM(I,J)	Elevation of bottom of upper layer (L)

Note: Data set 5 is required only for simulating unconfined conditions in the upper layer. Omit if not used.

DATA SET	COLUMNS	FORMAT	VARIABLE	DEFINITION
6	1-80	8F10.4	QRE(I,J)	Recharge rate in upper layer (L/T)

Note: Omit data set 6 if not used.

DATA SET	COLUMNS	FORMAT	VARIABLE	DEFINITION
7	1-80	8E10.3	RCG(I,J,K)	Stream leakage coefficient for gaining stream conditions (1/T) (for all layers)
8	1-80	8E10.3	RCL(I,J,K)	Stream leakage coefficient for losing stream conditions(1/T) (for all layers)

Note: RCG and RCL must be divided by grid-block area before entry.

DATA SET	COLUMNS	FORMAT	VARIABLE	DEFINITIONS
9	1-80	20F4.0	RHSS(I,J,K)	Elevation of constant stream stage(L)(for all layers)
10	1-80	20F4.0	HB(I,J,K)	Elevation of stream infiltration cutoff(L)(for all layers)
11	1-80	40I2	IZN(I,J)	Hydrogeologic unit numbers(only once for all layers)(no parameter card)

Note: If any of data sets 7-11 are not used, just insert a blank parameter card for each layer for each unused data set.

12 This data set is for hydrogeologic unit properties. There are 3 cards per unit, so 3(NZNS) cards needed. Each unit has the following 3 cards:

Card 1	1-2	I2	N	Hydrogeologic unit number
Card 2	1-10	F10.0	KXL(N)	Hydraulic conductivity in the x-direction in lower layer (L/T)
	11-20	F10.0	KYL(N)	Hydraulic conductivity in the y-direction in lower layer (L/T)
	21-30	F10.0	KZL(N)	Hydraulic conductivity in the z-direction in lower layer (L/T)
	31-40	F10.0	BZL(N)	Thickness of lower layer (L)
	41-50	F10.0	SZL(N)	Storage coefficient in lower layer (dimensionless)
Card 3	1-10	F10.0	KXU(N)	Hydraulic conductivity in the x-direction in upper layer (L/T)
	11-20	F10.0	KYU(N)	Hydraulic conductivity in the y-direction in upper layer (L/T)
	21-30	F10.0	KZU(N)	Hydraulic conductivity in the z-direction in upper layer (L/T)
	31-40	F10.0	BZU(N)	Initial saturated thickness of upper layer (L)
	41-50	F10.0	SZU(N)	Specific yield in upper layer (dimensionless)

DATA SET	COLUMNS	FORMAT	VARIABLE	DEFINITION
13	This data set is for multipliers to modify unit hydraulic conductivities according to topographic setting. There is one card per unit, so NZNS cards needed. Each card should be set up as follows:			
	1-5	F5.0	PMULT(I,1)	Multiplier for hilltop setting
	6-10	F5.0	PMULT(I,2)	Multiplier for upper-slope setting
	11-15	F5.0	PMULT(I,3)	Multiplier for middle-slope setting
	16-20	F5.0	PMULT(I,4)	Multiplier for lower-slope setting
	21-25	F5.0	PMULT(I,5)	Multiplier for valley-bottom setting
14	1-80	8G10.0	DELX(J)	Grid spacing in x-direction(L)
15	1-80	8G10.0	DELY(I)	Grid spacing in y-direction(L)
16	1-80	8G10.0	DELZ(K)	Grid spacing in z-direction(L) (Specify as 1)

Group IV: Parameters that change with the pumping period

The program has two options for the simulation period:

1. To simulate a given number of time steps, set TMAX to a value larger than the expected simulation period. The program will use NUMT, CDLT, and DELT as CODED. If NUMT is greater than 50 change the dimension of ITTO in subroutine STEP to the appropriate size.

2. To simulate a given pumping period, set NUMT larger than the number required for the simulation period (for example, 50). The program will compute the exact DELT (which will be $\leq$ DELT coded) and NUMT to arrive exactly at TMAX on the last time step.

Card 1 is required for every problem. The well cards and the additional pumping period data are used as desired.

CARD	COLUMNS	FORMAT	VARIABLE	DEFINITION
1	1-10	G10.0	KP	Number of the pumping period
	11-20	G10.0	KPM1	Number of the previous pumping period

Note: KPM1 is currently not used

	21-30	G10.0	NWEL	Number of wells for this pumping period
	31-40	G10.0	TMAX	Number of days in this pumping period
	41-50	G10.0	NUMT	Number of time steps
	51-60	G10.0	CDLT	Multiplying factor for DELT

Note: 1.5 is commonly used

	61-70	G10.0	DELT	Initial time step in hours

The following well cards are read only for the first pumping period but will automatically be used in all subsequent pumping periods.

	1-10	G10.0	K	Layer in which well is located
	11-20	G10.0	I	Row location of well
	21-30	G10.0	J	Column location of well
	31-40	G10.0	WELL(I,J,K)	Pumping rate (L^3/T), negative for a pumping well

For each additional pumping period, the following set of data is needed:

Card 1 Same as card 1, Group IV

Card 2 Card with multiplier for following recharge matrix (E10.3)

DATA SET 1 Recharge matrix for pumping period (8F10.4)