A Digital Model Approach to Water-Supply Management of the Claiborne, Clayton, and Providence Aquifers in Southwestern Georgia

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ABSTRACT

Management of ground-water resources can be effectively performed by state agencies responsible for issuing water-use permits that have operating numeric ground-water flow models for major aquifers. Proposed changes in pumpage can be simulated by such models to a sufficient degree of accuracy so as to provide the technical basis for decision making by management agencies. The Geologic Survey Branch of the Georgia Environmental Protection Division (EPD), with assistance from the United States Geological Survey (USGS), has developed a numeric ground-water flow model for the Claiborne, Clayton and Providence aquifers in southwestern Georgia to assist the Division with its water resource management responsibilities. The model utilizes the McDonald-Harbaugh modular quasi-three dimensional ground-water flow model code (MODFLOW). This code is capable of both steady-state and transient simulations. The model is calibrated to observed head and pumpage data through 1986. 1986 head and pumpage data are essentially unchanged through 1992. The model will be used by EPD to simulate potential changes in heads before issuing permits for any requested additional ground-water use in the affected aquifers.

The model is used to predict heads in the aquifers for four hypothetical ground-water scenarios, developed in consultation with the Director of EPD. If present pumpage (the Baseline Simulation) continues unchanged, the heads in the Clayton and Providence aquifers will continue to decline. Simulated response to a major two-year drought (the Drought Simulation) indicates that heads in all three aquifers would decline during the duration of the drought, particularly in areas of heavy irrigation pumpage, and that the recharge to the aquifers would be replaced by the withdrawal of large volumes of ground-water from storage in the aquifers. The long term effect of withdrawing one million gallons per day for industrial use from the Claiborne and from the Clayton aquifers is simulated as the third scenario (the Industrial Development Simulation). Such additional pumpage would likely lower the heads in the Claiborne, Clayton, and Providence aquifers significantly near the industrial well(s). Lesser effects would be widely distributed in the aquifers. The Clayton aquifer, already the most stressed aquifer in the system, would be even more adversely affected. The fourth situation involves the City of Albany, the largest municipal water user in the region. In this scenario, pumpage from the Claiborne, Clayton, and Providence aquifers in the general vicinity of Albany is reduced by 20 percent, in response to a plan to utilize the Upper Floridan aquifer to meet some of the City's future water needs. Such a reduction in pumpage would cause the heads in the Claiborne, Clayton, and Providence aquifers to rise in the Albany area.

The Upper Floridan, Claiborne, Clayton, and Providence aquifers in southwestern Georgia and southeastern Alabama are hydrologically interconnected, albeit not efficiently. Development of irrigation, industrial, and municipal wells in the region has resulted in declines in the potentiometric surfaces of the Claiborne, Clayton, and Providence aquifers when compared to predevelopment surfaces. Vertical leakage between aquifers is an important pathway of ground-water flow. The Claiborne aquifer, in particular, is well connected hydrologically with the overlying Floridan aquifer; and, as a result of this interconnection, additional ground-water resources may be developed at some locations. The Clayton aquifer, on the other hand, is poorly connected to the other aquifers, is heavily pumped in the region, and is not capable of supporting any significant additional pumpage in most parts of the region. The Clayton is somewhat better connected to the underlying Providence aquifer than it is to the overlying Claiborne aquifer; therefore, attempted additional development of the Clayton also would probably adversely affect the Providence and could adversely affect all three aquifers in places. The Claiborne, Clayton, and Providence aquifers are particularly heavily stressed in the Albany and Dawson areas where additional pumpage from these three aquifers is not recommended.

INTRODUCTION

General Background

Ground-water use in southwestern Georgia has increased significantly over the past few decades. Since the middle 1970's, combined increases in industrial, agricultural and municipal ground-water use have caused declines in ground-water levels in the deeper confined aquifers. The continued development of ground-water resources and the associated water-level declines, in conjunction with recent droughts, vividly demonstrate the need for proper and efficient management of these valuable resources.

This report describes the development and application of a digital model of ground-water flow for the three major confined aquifers of southwestern Georgia: the Claiborne, Clayton, and Providence aquifers. Although not the focus of the study, the Upper Floridan is included in the model. The general purpose of this digital model, therefore, is to improve understanding of ground-water flow in the confined aquifers and to facilitate efficient and informed resource management.

Specific elements of this study included: (1) development and calibration of a digital model that simulates ground-water flow in three vertically contiguous aquifers, and (2) application of this model to quantitatively describe pre-development, modern (1986), and hypothetical future ground-water flow conditions.

Figure 1 shows the study area in southwest Georgia and southeast Alabama. It covers approximately 7,425 square miles and includes all or parts of 30 counties in the two states. The study area was defined by the distribution and extent of the aquifer system of interest. The southwestern boundary of the study area is approximately defined by the western drainage divide of the Chattahoochee River in eastern Alabama. The southeastern boundary of the study area is approximately defined by the southern extent of the aquifer system. The northeastern boundary of the study area is the approximate drainage divide between the Flint and Ocmulgee Rivers in southwestern Georgia. The northwestern boundary of the study area is approximated by the inner margin of the Coastal Plain.

The study area is drained by two of Georgia's largest rivers. The Chattahoochee River separates Alabama and Georgia and drains the western part of the study area. The Flint River drains the eastern part of the study area. Near the Georgia-Florida State line, the Flint River joins the Chattahoochee River to form the Appalachicola River, which flows southward across the Florida panhandle to the Gulf of Mexico. The Chattahoochee River has been dammed at Fort Gaines and forms the Walter F. George Reservoir. The Flint River has been dammed at the juncture of Crisp, Lee, and Worth Counties forming Lake Blackshear and at Albany forming a Georgia Power Company reservoir. Jim Woodruff Dam, creating Lake Seminole, is at the confluence of the Chattahoochee and Flint Rivers.

Climate and Runoff

Southwest Georgia and southeast Alabama generally have short, mild winters and hot, humid summers. Winter temperatures generally are above freezing, but do occasionally drop below 20 degrees F. Summer temperatures commonly are above 90 degrees F and temperatures above 100 degrees F are not rare. Precipitation in the study area occurs almost completely as rainfall, and ranges from about 46 to 54 inches per year (Carter and Stiles, 1983). Abundant rain occurs during winter months with a gradual increase to a maximum in February or March. Heaviest rains normally fall during July and August due to frequent summer thunderstorms. October and November are the driest months. A secondary period of diminished rainfall is in April and May. Annual runoff in southwestern Georgia is highly variable, and ranges from 12 to 24 inches per year.

Previous Investigations

The geology and hydrogeology of southwestern Georgia have been previously studied in either a localized or a general fashion. Stephenson and Veatch (1915) described the geology of the Georgia Coastal Plain by formation, including the areal extent, lithology, stratigraphic position, strike and dip of beds, thickness of rock units, paleontology, and structure. Cooke (1943) described the general geology of the Georgia Coastal Plain. Herrick (1961) advanced the knowledge of the geologic framework of the Coastal Plain of Georgia by describing detailed lithologic logs. Marsalis and Friddell (1975) gave an overview of the lithologic units exposed in the Chattahoochee River Valley area, including discussions of facies changes along strike and down dip. Gibson (1982) differentiated six Paleocene and Middle Eocene marine units in eastern Alabama and western Georgia, including composition, fossil assemblage, and descriptions of nonmarine and marine transitions.

Numerous investigations of the ground-water hydrology were undertaken beginning in the early 1950's as the demand for ground-water increased.

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As in most ground-water studies, investigation of the geology was commonly a substantial part of these efforts. In 1958, Wait described the stratigraphy and ground-water availability in Crisp County. Wait (1960 a, b, c,) also described the geology and ground-water resources in Calhoun, Clay, and Terrell Counties, and discussed the geology and ground-water resources of Dougherty County (1963). Owen (1963) compiled existing data to extend the knowledge of ground-water conditions in Lee and Sumter Counties. Stewart (1973) reported Clayton aquifer hydraulic characteristics which were estimated from aquifer tests performed during the design and construction of the Walter F. George Lock and Dam in the Ft. Gaines area. Pollard and Vorhis (1980) described the geohydrology of the Cretaceous aquifer system in Georgia. Hicks and others (1981) evaluated the development of ground-water resources in the Albany area. Ripy and others (1981) published an interim report on the hydrogeology of the Clayton and Claiborne aquifers in southwest Georgia. McFadden and Perriello (1983) conducted a general study of water-level trends, ground-water quality, ground-water use, aquifer geometry, lithologic and hydrologic characteristics, and recharge and discharge mechanisms of the Clayton and Claiborne aquifers in southwest Georgia. Clarke and others (1983, 1984) described and evaluated the effects of water use on the ground-water systems of the Providence and Clayton aquifers, respectively. In 1984, the Geologic Survey compiled an atlas (Arora, editor) describing aquifers in the Georgia Coastal Plain, including isopach, structure-contour, and potentiometric surface maps as well as cross-sections. Davis (1987) described the stratigraphic and hydrogeologic framework of the Cretaceous, Tertiary, and Quaternary Systems in Alabama to aid in delineating aquifers and confining units within the Alabama Coastal Plain. Water-level, water-use, and water-quality information on the Clayton and Claiborne aquifers between 1982 and 1986 has been compiled (Long, 1989a). Ground-water flow and stream-aquifer relations in the outcrop areas of the Coastal Plain sediments were quantitatively described by Faye and Mayer (1990).

Hayes and others (1983) developed a digital finite-difference ground-water flow model of the Principal Artesian (Floridan) aquifer in the Dougherty Plain area of southwest Georgia. The United States Geological Survey (USGS), as part of their Regional Aquifer System Analysis (RASA) program, has two ground-water flow modeling studies pertinent to this study. Maslia and Hayes

(1988) defined the regional flow system of the Floridan aquifer system in the Dougherty Plain. Faye and Mayer (1990) developed a ground-water flow model of regional ground-water flow in the Coastal Plain of Georgia. Although Faye and Mayer's study encompassed the entire hydrogeologic framework of the Coastal Plain, it primarily addressed the deep, regional component of the ground-water flow system, and was necessarily of rather large scale.

A description of the stratigraphic and hydrogeologic framework of southwestern Georgia resulting from the previous studies mentioned in this section, and on which the conceptual and digital (or numeric) models presented in this report are based, are included in this report as Supplement I.

Acknowledgments

The development of a digital model for the Claiborne, Clayton, and Providence aquifer systems was begun by Anna Long of the Georgia Geologic Survey with the preparation of Hydrologic Atlas 19 (1989a). Long (1989b) proceeded with the development of a steady-state digital model. Lee Gorday expanded upon Long's work and developed and calibrated a transient model and used the model to prepare predictive scenarios for various water-supply management options for southwestern Georgia (this report). Model development was carried out by the Georgia Geologic Survey to assist the Water Resources Management Branch of EPD in its assigned role of regional ground-water use management. The model was developed under the guidance of the USGS, Georgia District Office. The USGS provided technical assistance and guidance on a day-to-day basis through model calibration and the manuscript.

Scope of Work

This report provides the results of an application of the McDonald-Harbaugh (1988) ground-water flow model (MODFLOW) of the Claiborne, Clayton, and Providence aquifers to four ground-water management simulations. For a description of the hydrogeological assumptions, mathematical assumptions, and computer codes, the reader is referred to their work.

No field studies were performed for this study. Data entered into the model are direct measurements reported by others, estimates reported by others, calculated values made by the authors or by others, or estimates believed by the authors, after consultation with the USGS, to be reasonable.

All modelling was done at the offices of the

Georgia District of the USGS using their computer facilities onto which MODFLOW had been installed.

CONCEPTUAL MODEL

Existing field data, previously published information on the aquifers, and theoretical concepts of ground-water flow were synthesized to develop a conceptual model of ground-water flow within the interconnected Floridan, Claiborne, Clayton, and Providence aquifers. The conceptual model addresses ground-water flow in the aquifer system from the point of initial recharge to the system to the point of ultimate discharge. The conceptual flow model developed for the present study closely follows the conceptual model presented by Faye and Mayer (1990) as a part of their digital model analysis that included additional aquifers and larger study area. The present study focuses on both the regional and intermediate flow systems, whereas the Faye and Mayer study focused strictly on the regional flow system. Figure 2 is a schematic representation of the aquifer system under investigation.

The basic premise behind the conceptual model is that precipitation recharges the Claiborne, Clayton, and Providence aquifers in their outcrop areas in the upper Coastal Plain. Ground water then flows to the south-southeast down-gradient through the aquifers, which in turn become confined. Because the older aquifers crop out at higher elevations, the head in older aquifers is generally higher than the head in younger aquifers. This means that under predevelopment conditions there was an upward component of ground-water flow, across the confining (lower hydraulic conductivity) units (e.g. there was flow from the Providence to the Clayton, from the Clayton to the Claiborne, and from the Claiborne to the Floridan—lowering of head as a result of pumpage, however, could reverse such gradients).

Ground-water flow in an aquifer recharge area is dynamic and complex and is controlled largely by topography and stream-aquifer relations. Toth (1963), in describing the flow of ground water in an unconfined area with local relief, introduced the concept of local, intermediate, and regional flow systems (Figure 3). The aquifers are unconfined and ground-water flow within each aquifer has significant vertical as well as horizontal components. The hilly topography of the aquifer recharge areas such as occurs in the western part of the upper Coastal Plain of Georgia, produces numerous subsystems within the major flow system. Most of the water that recharges the ground-water

system flows to the closest stream and discharges; this is termed local flow. Local flow is characterized by short, shallow flow paths. Water that enters the system at the highest point and discharges to the stream or river at the lowest point in the area under investigation (or that flows downdip beneath younger semi-confining units) is known as regional flow. Regional ground-water flow follows the longest and deepest flow paths. Between these extremes is the intermediate flow system. Water in the intermediate flow system bypasses at least one local discharge site along its flow path (Toth, 1963). These terms are dependent to a large degree on scale, (e.g. Toth's concept of regional flow in unconfined outcrop area is not the same as regional flow throughout an entire aquifer system).

Fluctuations in climatic conditions, such as droughts, affect the local flow system with its short, shallow flow paths, to a greater degree than the intermediate and regional flow systems. Because the purpose of this study was to develop a model for use in managing the ground-water resource (e.g. ground-water withdrawal permits), the conceptual model as well as the digital model focus on the intermediate and regional ground-water flow systems. The local flow system is beyond the scope of the management objective. For the purpose of this study, it was assumed that the drought of 1954, one of the severest on record, depleted flow in the local flow system.

Precipitation that falls in the area of outcrop of the aquifers may run off or infiltrate the ground surface. A small amount may be held in puddles or ponds where it may evaporate. Much of the water that infiltrates the ground is transpired back to the atmosphere by plants. Water that percolates to the water table recharges the ground-water system. This is the ultimate source of water to the four aquifers under consideration in this study. The assumption is made that all streams that cross the outcrop areas either gain water from the aquifers by way of baseflow, or have no significant net loss of water to the aquifers. Although this assumption may not hold for the local flow system, it is probably valid for the intermediate and regional flow systems that are the focus of this study. Recharge to the aquifers is greatest in the interstream divides and lowest in the vicinity of streams.

Water that recharges the aquifer may follow a number of flow paths. Most of the water that recharges the ground-water system is discharged to rivers and streams, as described above. Water that does not discharge to streams flows down the dip of the aquifer (in which it recharged) or moves

vertically to another aquifer as leakage.

Vertical leakage between aquifers, prior to development, is conceptualized as being downward in areas of net recharge and upward in areas of net discharge. Between these areas, ground-water flow is essentially horizontal with little vertical movement. In the updip part of the study area, most vertical leakage is downward, the exception being in the vicinity of streams receiving discharge. This is corroborated by comparing the map of the potentiometric surface of the Claiborne aquifer (Figure 4) (McFadden and Perriello, 1983) with the potentiometric surface map of the Clayton aquifer (Figure 5) (McFadden and Perriello, 1983) of the same time period. Comparison of these maps indicates that the gradient between the Claiborne and Clayton aquifers generally is downward in the updip area of the study and generally is upward in the downdip area of study. Data are lacking to describe the head gradient in the entire downdip portions of the study area (e.g. south of Miller and Mitchell Counties). Head data that are solely from the Providence aquifer are sparse, which precludes a comparison between potentiometric surfaces of the Providence and Clayton aquifers. Because of the high hydraulic conductivity of the Providence, Clayton, and Claiborne aquifers relative to the confining units, flow is assumed to be chiefly horizontal in the aquifers and vertical through the confining units.

The Flint and Chattahoochee Rivers influence ground-water flow in the downdip portion of the Claiborne and Clayton aquifers, as they do in the updip area. In Georgia, an approximate north-south ground-water flow divide has developed where ground water on one side flows west toward the Chattahoochee River; but on the other side, ground water flows east toward the Flint River. Because heads are lower on either side of this divide, there probably is no flow of water across the divide. The ground-water flow divide in the Clayton aquifer can be seen in Figure 5 extending from eastern Randolph County southward through central Calhoun County, to Miller County. Similar divides appear to exist between the Flint and the Ocmulgee Rivers and between the Chattahoochee and the Chochtawhatchee Rivers. The location of the ground-water flow divides can change with time in response to changes in hydrologic conditions such as recharge and pumpage. The eastern boundaries of the area of this study generally conform to the divide east of the Flint River for the Claiborne, Clayton, and Providence aquifers prior to development of large ground-water pumpage. The western boundary of the study area, in Alabama

corresponds to the apparent divide west of the Chattahoochee River for the Providence and Clayton aquifers prior to development of large ground-water pumpage.

Downdip facies changes that result in the decrease in the hydraulic conductivity of the Claiborne, Clayton, and Providence aquifers all occur in the same general area (see Supplement I). Although some water may continue to flow down dip, it is unlikely that much water flows across this boundary. Prior to the installation of large numbers of wells in the aquifers, the water flowing laterally in these aquifers would move downdip, then vertically upward (Faye and Mayer, 1990). After the water moved upward into the Floridan aquifer, it would be discharged to a stream or would flow laterally within the Floridan aquifer. The development of large quantities of pumpage (e.g. primarily irrigation) from the aquifers has led to a reduction in the upward flux in some down-dip areas. Locally, vertical gradients have been reversed. The increase in ground-water withdrawals probably has resulted in the lateral shifting of some of the ground water divides.

DIGITAL MODEL ANALYSIS

Introduction

Water-level declines resulting from increasing ground-water withdrawal and a series of droughts have demonstrated a need for a better understanding of ground-water flow in the Claiborne, Clayton, and Providence aquifers in southwest Georgia. In response to this need, and in anticipation of future conflicting demands for the finite water resources of the region, a digital ground-water flow model was constructed to aid in the informed management of this vital resource. Details of model development and calibration and the results of sensitivity analysis are presented in this report as Supplement II.

The primary focus of the digital model simulation is flow in the Claiborne and Clayton aquifers in the area of their greatest use. In order to adequately address these issues, the model had to include the Upper Floridan aquifer as a constant-head source/sink above the Claiborne aquifer, and the Providence aquifer as an active layer below the Clayton aquifer. In addition, the lateral boundaries of the model were extended, in most areas, well beyond the active use of the aquifers in Georgia to have stable conditions at the boundaries.

A digital ground-water flow model computes the potentiometric head in an aquifer over space and, for transient simulations, time. Heads are

computed by solving ground-water flow equations, given the distribution of hydraulic parameters, boundary conditions, and initial conditions. Analytical solutions to these equations are available for a range of relatively simple boundary conditions. Digital models are useful in situations where the boundary and initial conditions are complex, and where hydraulic properties or characteristics vary through space.

A model of ground-water flow conditions prior to development was constructed and calibrated against measured heads, estimated ground-water discharge to streams, and estimated flux at the boundaries of the model (Long, 1989b). The model was used in the steady-state mode to simulate conditions prior to the development of the aquifers having high-yielding wells. In the steady-state mode, conditions within the flow system do not change with time. The head distribution from steady-state simulations of the model were used then as the initial head distribution in transient simulations, where pumpage changed through time. Model parameters were adjusted to provide a closer match between the heads and fluxes simulated by the model in the steady-state mode and observed heads, estimated discharge to streams and estimated boundary fluxes.

The simulated heads and model parameters (including boundary conditions) from the steady-state simulation were used along with additional parameters (storage and pumpage) in the transient simulation. Transient simulations were constructed for fifteen stress periods between 1900 and 1986 (Table 1). (Note: Heads were fixed in the Upper Floridan aquifer (A1); this was deemed reasonable as the Upper Floridan aquifer in southwest Georgia is recharged every year and water level declines are only short term (i.e. a few months).) The model heads computed in the transient simulations were compared to observed heads measured at seven times during the period of simulation. Observed heads sufficient for comparison were available for all aquifers at times corresponding to period 2 (1945-1959), period 8 (1978 and 1979), period 13 (1984) and period 15 (1986). Observed heads for the Providence aquifer were available for period 9 (1980) and for the Claiborne and Clayton aquifers for periods 10 and 11 (1981 and 1982), respectively. Details of the development, calibration, and sensitivity analysis of the transient model are in Supplement II of this report.

Hydrographs of simulated head were prepared for various stress periods and compared to observed water-level fluctuations. Changes in any

parameters, other than storage or pumpage, required the change to be implemented in the steady-state mode, and a complete evaluation was made of the match between simulated conditions and observed and estimated conditions prior to implementation in the transient mode. This loop approach was used until an acceptable match was achieved between simulated conditions and observed and estimated conditions for the model in both the steady-state and transient modes.

Model Description

The McDonald-Harbaugh modular quasi-three dimensional ground-water flow model code (MODFLOW), which is capable of both steady-state and transient simulations, was used in this study (McDonald and Harbaugh, 1988). This model is based on a finite difference approach, which uses a rectangular grid, either uniform or variably-spaced. Within each cell of the grid, the hydraulic parameters are uniform. Fluxes simulated in each cell (such as recharge, well pumpage, and discharge to rivers) are distributed evenly over the cell. Potentiometric heads calculated by the model represent the head over the entire area of the cell.

Three-dimensional flow is simulated by linking two-dimensional (lateral) flow in each layer with one-dimensional (vertical) flow between the layers as a representation of leakage. The model code constructs an equation describing ground-water flow for each node. These simultaneous equations are solved through an iterative process of matrix algebra known as the strongly implicit procedure (SIP). The procedure is described in detail in the model documentation (McDonald and Harbaugh, 1988). Wang and Anderson (1982) present an overview of various solution techniques including SIP.

Relation of Digital Model to Conceptual Model

A finite-difference grid of 57 rows and 85 columns was used to subdivide the study area (Figure 6). The grid was oriented so that the predominant direction of ground-water flow would be parallel to the columns of the grid. The columns are aligned 30 degrees west of north. Grid spacing was either one or two miles for both rows and columns. Cell areas are 4 square miles for cells with both row and column spacings of 2 miles, 1 square mile for cells with both row and column spacings of 1 mile, and 2 square mile for 1x2 mile cells. The model area is bounded by either specified head and no-flow conditions both laterally and vertically. The specific application of these boundary conditions is discussed for each

layer in Supplement II of this report.

The digital flow model is based upon the conceptual flow model described previously. The general inter-relationship between aquifers and semi-confining units and regional stratigraphy is shown in Figure 7.

The Upper Floridan aquifer is represented by model layer A1, and is treated as a source-sink. Model layer A2 represents the Claiborne aquifer. The Clayton and Providence aquifers are represented by model layers A3 and A4, respectively. Flow across the confining units is simulated by one-dimensional flow based on the simulated heads in the adjacent layers and the leakance (vertical hydraulic conductivity divided by confining unit thickness). The confining unit between the Floridan and Claiborne aquifers is represented by C1 leakance. The Claiborne-Clayton and Clayton-Providence confining units are represented by C2 leakance and C3 leakance, respectively.

The digital flow model in this report is designed to simulate only the intermediate and regional ground-water flow systems. Simulation of local variation in head is not possible using the cell size in this model. Additionally, by addressing only the regional and intermediate flow systems, the independent estimate of flux to rivers and streams can be used to aid in the calibration of the model. Recharge as used in the digital model differs from the common concept of recharge. Only recharge to the intermediate and regional flow systems is considered in the model. Total recharge, therefore, is considered an upper limit to the recharge used in the digital model.

Streams and rivers, which had significant flow during the 1954 drought, are considered in the digital model to estimate aquifer contributions in base flow. Streams that are simulated are identified in Appendix A.

PREDICTIVE MANAGEMENT SCENARIOS

General

One of the purposes in developing the digital model of the Claiborne, Clayton, and Providence aquifers is to develop a tool for use in managing the ground-water resource. Four predictive scenarios or simulations were developed to demonstrate the usefulness of the model and to assess the response of the ground-water system to several hypothetical changes in pumpage. The four scenarios are: (1) The Baseline Simulation, (2) The Drought Simulation, (3) The Industrial Development Simulation, (4) The City of Albany Floridan Usage Simulation. For these four simulations, model parameters, including boundary conditions, were unchanged from transient simulations. The results of a simulation of a hypothetical change to the ground-water system are commonly assessed by examination of the trend and magnitude of changes in simulated head. In a system as dynamic as the Claiborne, Clayton, and Providence, changes in flux within the system and at the boundaries of the digital model also are of importance.

Baseline Simulation

The first predictive scenario simulates the response of continuing the model for five years at the pumpage rates similar used in the calibration of the model. This simulation represents a baseline or status-quo condition. Municipal and industrial pumpage are continued at the rates used in period 15 (1986) of the calibration simulations (see Table 1 and Supplement II). Irrigation pumpage is assigned a value that approximates the average pumpage for irrigation used in periods 10 through 15. The starting heads for the predictive simulations are the heads at the end of the calibration simulation.

In the Baseline Simulation, simulated heads generally decline in areas having large withdrawals for municipal and industrial uses during the first year. Simulated heads rise in areas with large withdrawals for irrigation. This rise in heads is the result of the average irrigation withdrawal being smaller than the irrigation withdrawal for period 15, the last stress period of the calibration period. The changes in head are relatively small for layers A2 and A4. In layer A2, the simulated head ranges from six feet higher to three feet lower at the end of the first year of the Baseline Simulation compared to heads at the end of the calibration period. Simulated heads decline across all of layer A4, with the maximum decline being less than six feet. Withdrawal for irrigation is much smaller in layer A4 than in layers A2 and A3; therefore, the reduced irrigation withdrawal in layer A4 has little impact on simulated heads. Simulated heads in layer A3 decline slightly over much of the area of the model. The maximum decline is less than six feet. A number of isolated areas are identified where simulated heads rose in response to the decreased withdrawals for irrigation. Where a number of irrigation systems are within a single cell, the rise in simulated head is quite large. The rise is as great as 23 feet in one cell. The area over which the simulated head rose was quite restricted in comparison to layer A2.

Simulated heads at the end of the fifth year of the Baseline Simulation are similar to those at the

end of the first year of the simulation. Large areas in layer A2 have simulated heads that are higher at the end of the fifth year than at the end of the calibration period; however, the area is smaller than that at the end of the first year of the simulation. The maximum decline in simulated head in layer A2 is about seven feet. Figure 8 shows the simulated potentiometric surface in layer A2 at the end of the five-year Baseline Simulation. Simulated heads in layer A3 at the end of the fifth year of the simulation are significantly lower than at the end of the first year. Drawdown from the end of the calibration period is as great as 16 feet. Some areas of layer A3 continue to have simulated heads that are higher than at the end of the calibration period; but these are less numerous and of lower magnitude than at the end of the first year of the simulation. The simulated potentiometric surface in layer A3 at the end of the Baseline Simulation is shown in Figure 9. Simulated heads in layer A4 are as much as 16 feet lower at the end of the simulation (Figure 10) than at the end of the first year or at the end of the calibration period.

Simulated fluxes within the ground-water flow system and at the model boundaries had changed relatively little at the end of the Baseline Simulation from the simulated fluxes at the end of the calibration period. Net vertical flux across confining unit C3 increases from 15.9 cubic feet per second (cfs) at the end of the calibration period to 18.4 cfs at the end of the Baseline Simulation; this is within the range of values simulated at other stress periods in the calibration simulation. The simulated net vertical flux across confining units C1 and C2 increases to 6.7 and 9.7 cfs, respectively. These values are higher than the simulated flux at any stress period in the calibration simulation. Changes in horizontal constant-head fluxes and discharge to rivers and streams are minimal.

The Baseline Simulation was developed not only to assess the effects of continuing pumpage at current values, but also to provide a basis for comparison with the other predictive scenarios. By comparing the results of the other scenarios to the Baseline Simulation, the effects of the modeled change can be isolated from the effect of continued pumpage at existing levels.

Drought Simulation

Drought conditions were simulated using reduced recharge rates and increased pumpage for irrigation. The recharge rate was reduced to 75 percent of the calibrated value, a reduction of 142 cfs. This reduction is similar in magnitude to the

reduction in precipitation in a drought having a 10-year recurrence interval. The pumpage for irrigation was arbitrarily assigned a value of 150 percent of the irrigation used in the Baseline Simulation. The pumpage in layer A2 represents an increase in pumpage of 25.5 cfs over the pumpage in the Baseline Simulation. Increases for layers A3 and A4 are 12.1 and 0.7 cfs, respectively.

The change in simulated head in layer A2 at the end of the second year of the Drought Simulation (compared to simulated heads at the same time in the Baseline Simulation is shown in Figure 11. There are large areas having drawdowns of 5 feet or more. The maximum difference between the simulated head for the Drought Simulation and the Baseline Simulation is 24 feet. Large drawdowns are restricted to small areas. Head differences between the drought and baseline simulations in layer A3 are shown in Figure 12. Drawdowns in layer A3 are much greater than in layer A2 despite the fact that the amount of additional withdrawal compared to the Baseline Simulation is much smaller. The area having a simulated drawdown of 5 feet or more is significantly larger for layer A3. Drawdowns in layer A4, shown in Figure 13, cover a large area, similar to layer A3. The maximum drawdown is 18 feet, but this is produced by a very small additional withdrawal. Much of the difference in layer A4 is due to leakage of water to layer A3.

The largest change in simulated flux compared to the Baseline Simulation is the movement of water from storage. The increase in water being removed from storage is 150 cfs at the end of two years of drought. The large change is due to the reduction in recharge. Upward vertical flow from layer A4 to A3 increases 4.8 cfs. Increased downward flow from layer A1 to layer A2, coupled with a decrease in upward flow from A2 to A1 results in a net change in flow across confining unit C1 of 1.9 cfs. Vertical flow, across confining unit C2, changes little between the Drought and Baseline Simulations. Fluxes from specified-head boundary cells change little in layers A3 and A4. Simulated fluxes from the specified-head boundary cells in layer A2 into the model area increase 2.7 cfs.

Industrial Development Simulation

The effects of a hypothetical industrial development were simulated. Withdrawals of 1.54 cfs (1 Mgal/d) were taken from both layer A2 and layer A3 at row 37 and column 72 (2 Mag/d total). This location corresponds to a site along the Flint River in Lee County northeast of Leesburg. A withdrawal of 3.1 cfs (2 Mgal/d) is relatively typical

for many industrial purposes; thus the simulation is considered relatively conservative. The withdrawal in this simulation represents a 2 and 4 percent increase in total withdrawal for layers A2 and A3, respectively.

Simulated heads in each layer decline in the area of the simulated industrial development compared to the Baseline Simulation. The drawdown due to the simulated industrial development in layer A2 after 5 years of pumpage is shown in Figure 14. The maximum drawdown is 22 feet at the cell in which the well is located. Drawdown in layer A2 decreases markedly within a few cells of the simulated development. The area having drawdowns of 5 feet or more is relatively small. Drawdown in layer A3, shown in Figure 15, is much greater than was noted in layer A2. The maximum drawdown is 46 feet. The area having a drawdown of 5 feet or more is large. Although there was no change in simulated pumpage in layer A4, drawdown did occur due to the pumpage and drawdown in layer A3. Drawdown in layer A4 (Figure 16) is as much as 11 feet. Although the maximum drawdown is small, the area having a drawdown of 5 feet or more is large.

Changes in simulated flux between the Baseline Simulation and the simulation of the industrial development are relatively small, chiefly because of the small change in pumpage (3.1 cfs). Almost half of the additional withdrawal (1.4 cfs) is being removed from storage. Boundary flux from specified-head cells changes very little in layer A3. In layers A2 and A4, flux into the model from specified head cells increases and flux out of the model decreases. The net change is 0.5 cfs for layer A2 and 0.4 cfs for layer A4. Simulated vertical fluxes across the confining units also respond to the additional pumpage. An additional 0.4 cfs leak downward across C1. A combination of decreasing flux from layer A3 to layer A2 and increasing flux from A2 to A3 results in a net change of 0.2 cfs in the flux across C2. The pumpage in layers A2 and A3 results in an increase in the upward flux across C3 of 0.8 cfs.

The City of Albany Floridan Aquifer Usage Simulation

Use of the Upper Floridan aquifer to reduce the demand on the Claiborne, Clayton, and Providence aquifers is an option available to the City of Albany. The effects of a shift in pumpage from the Claiborne, Clayton, and Providence aquifers to the Floridan aquifer was simulated by reducing the City of Albany's pumpage in layers A2, A3, and A4 by 20 percent. Pumpage from the Floridan aquifer is not simulated because the equivalent layer (A1) is simulated by specified heads. The reduction in pumpage from the baseline simulation is 3.3, 1.4, and 0.6 cfs for layers A2, A3, and A4 respectively.

Simulated heads resulting from the reduction in pumpage are considerably higher than the simulated heads in the Baseline Simulation in the area of Albany. The difference in simulated head between the Baseline Simulation and the reduced pumpage simulation for layer A2 is shown in Figure 17. The positive numbers indicate a rise in simulated head. The maximum rise is 26 feet. Figure 17 also indicates that the simulated head rose at least 10 feet over a large area. The difference in simulated heads in layer A3 is shown in Figure 18. It is important to note that the maximum rise in simulated head for layer A3 is 32 feet, which is substantially greater than the rise in layer A2, even though the decrease in pumpage in A3 is less than half the decrease for layer A2. The area with a rise of 10 feet or more is slightly larger for layer A3 than for layer A2. The change in simulated head for layer A4 is shown in Figure 19. The maximum rise is 22 feet. The area with a rise in simulated heads of 10 feet or more is quite similar to the area for layer A3.

Significant changes in flux occur as a result of the reduced pumpage in layers A2, A3, and A4. The rate of removal of water from storage drops 2.4 cfs from the baseline rate at the end of the five-year simulation. Little water is entering storage at the end of the simulation. Flux into storage at the end of the first year of the simulation is 2.0 cfs higher than the rate at the same time of the Baseline Simulation. Vertical flux from layer A1 to A2 decreases, whereas the flux from A2 to A1 increases, resulting in the net flux across confining unit C1 decreasing by 1.2 cfs. The simulated flux from layer A4 to A3 decreases by 0.5 cfs from the Baseline Simulation. Flux across confining unit C2 does not change significantly. A combination of decreasing rates of water entering layer A2 and increasing rates of water leaving the layer results in the simulated net flux from specified-head boundary cells decreasing 0.9 cfs. The net change in simulated flux from specified-head cells in layers A3 and A4 is very small.

INTERPRETATIONS AND CONCLUSIONS

The Upper Floridan, Claiborne, Clayton, and Providence aquifers comprise an interrelated aquifer system in southwest Georgia and in the adjacent area of Alabama. Development of wells

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to supply water for municipal and industrial uses and for irrigation have resulted in declines in the potentiometric surface in these aquifers. A digital (or numeric) flow model was developed as a tool to assist in the management of this vital resource. The model used was a finite difference modular model published by McDonald-Harbaugh (1988).

The main focus of the digital model was intermediate and regional ground-water flow in the Claiborne and Clayton aquifers. In order to model flow in these aquifers, it was necessary to model the interaction between these aquifers and the adjacent aquifers. The Floridan aquifer, which overlies the Claiborne aquifer, was simulated as a specified-head layer. The Providence aquifer, which underlies the Clayton aquifer, was included as an active layer (simulated aquifer).

The model was used in the steady-state mode to simulate pre-development conditions and in the transient mode to simulate conditions between 1900 and 1986. Calibration of the model in the steady-state mode was conducted by comparison of the model results to observed heads, estimates of ground-water discharge to rivers, and estimated fluxes at the model boundaries. Calibration of the model in the transient mode consisted of comparison of simulated heads with observed heads at seven different times, and comparisons of simulated hydrographs with observed hydrographs.

The relatively small difference between simulated and observed heads along with the close match between estimated and simulated ground-water discharge to rivers, estimated and simulated boundary fluxes is deemed to be indicative that the model is well calibrated. Moreover, the close congruence between simulated and observed hydrographs indicates that the model is well validated. Indication that the model can be used for predictive purposes is provided by the fact that it is calibrated and validated.

The results of the model simulations indicate that vertical leakage is an important pathway of ground-water flow. The importance of vertical leakage in the understanding of the overall ground-water flow system is critical. Unfortunately, estimation of the rate of movement of ground water across confining units is very difficult, and has not been measured within the study area. Measurement of the leakance of the confining units between the aquifers in the area of this study could provide information useful in refining the hydrologic parameters used in the digital model.

The results of the sensitivity analysis indicate that the model is most sensitive to changes in pumpage rates, recharge, and transmissivity. The

rate of recharge to the aquifers is very difficult to measure. Furthermore, the focus of this model on the intermediate and regional flow systems makes the estimation of recharge for the purpose of this model difficult. The distribution of transmissivity estimates from specific capacity values is sparse for the Claiborne and Clayton aquifers, and almost non-existent for the Providence aquifer. Additional measurements of transmissivity are needed for each of the aquifers included in this study. The pumpage data used in the calibration of the flow model are based on estimates and projections. The quality of the match between simulated and observed heads, especially with the independent verification provided by the hydrograph comparisons and comparison of simulated and estimated fluxes indicate that the estimates of these parameters are reasonable. Measurement of pumpage for irrigation (in contrast to estimation) and defining the contribution of each aquifer to the flow from multi-aquifer wells would significantly improve the predictive capabilities of this model.

The results of the calibration and predictive simulations indicate that the Claiborne aquifer is well connected to the overlying Upper Floridan aquifer. This connection is indicated by the changes in leakage across confining unit C1 as a result of changes in stress in layer A2. Large changes in simulated pumpage from layer A2 resulted in only moderate changes in simulated head, thus suggesting that additional ground-water can be developed from the Claiborne aquifer. This probably represents a "real-world scenario" because layer A1 probably can supply more water in nature than in the model, in which A1 heads would be allowed to decline as a result of pumping in layer A2. Additional withdrawal in the Albany area, however, is not recommended. The amount of additional water that can be withdrawn depends on where the withdrawal is located and the allowable impact upon other ground-water users. The maximum acceptable increase in ground-water use from the Claiborne aquifer is likely to be small compared to the existing withdrawal.

Large declines in the simulated head of the Clayton aquifer occurred over the period of the calibration simulation. Small increases in pumpage from layer A3 resulted in large declines in simulated heads in the predictive simulations. This response to changes in pumpage rates indicates that the Clayton aquifer is heavily stressed and is not capable of supporting significant additional withdrawal in most areas. Even small additional withdrawals are likely to produce unacceptable drawdowns at nearby users.

The simulation of an additional withdrawal in combined layers A2 and A3 resulted in significant changes in simulated head in layer A4. This indicates that the Clayton and Providence aquifers are reasonably well connected and reinforces the conclusion that further development of the Clayton aquifer would have an unacceptable effect on the entire flow system. The Albany and Dawson areas are particularly heavily stressed. Additional withdrawal from the Claiborne, Clayton, and Providence aquifers in these areas generally is not recommended.

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Stress Period	Time Steps	Pumpage (cfs)			
		A2	A3	A4	Total
SPI 1900-1955	1	3.08	2.68	1.97	7.73
SP2 1944-1959	4	7.56	8.72	6.05	22.33
SP3 1960-1963	4	12.9	8.88	2.96	24.7
SP4 1964-1967	4	9.81	9.94	3.18	22.93
SP5 1968-1971	4	12.0	11.2	3.88	27.1
SP6 1972-1975	4	12.6	12.8	4.06	29.5
SP7 1976-1977	2	26.5	18.8	5.78	51.1
SP8 1978-1979	2	25.5	17.8	6.21	49.5
SP9 1980	1	27.0	18.8	6.36	52.7
SP10 1981	1	87.2	55.5	8.19	150.9
SP11 1982	1	54.9	26.2	5.35	86.5
SP12 1983	1	80.5	43.2	5.86	129.6
SP13 1984	1	62.8	30.4	5.34	98.5
SP14 1985	1	51.9	23.2	5.16	80.3
SP15 1986	1	94.6	48.0	6.81	149.4

Table I. Stress periods and pumpage utilized in the calibration of transient model.
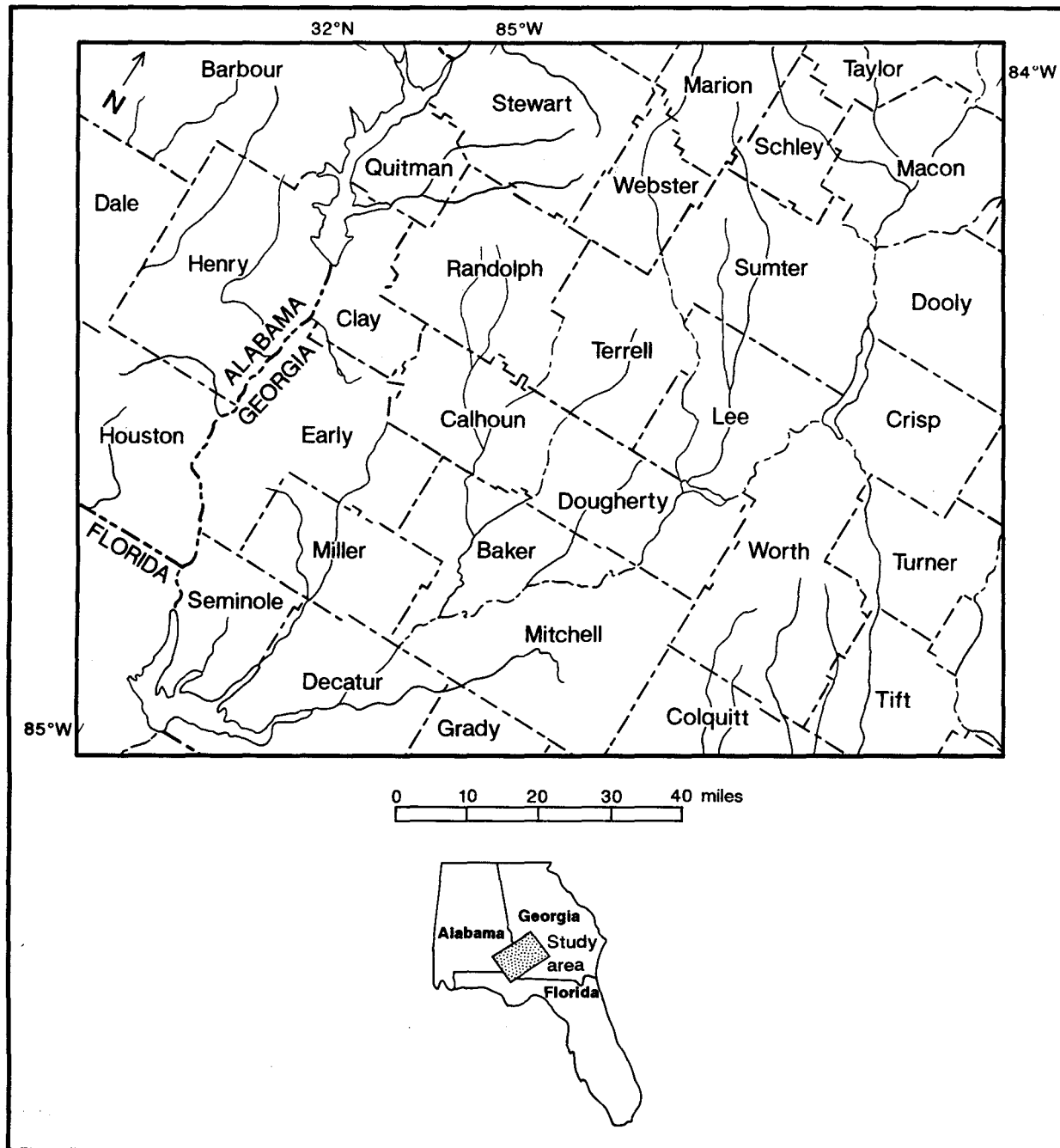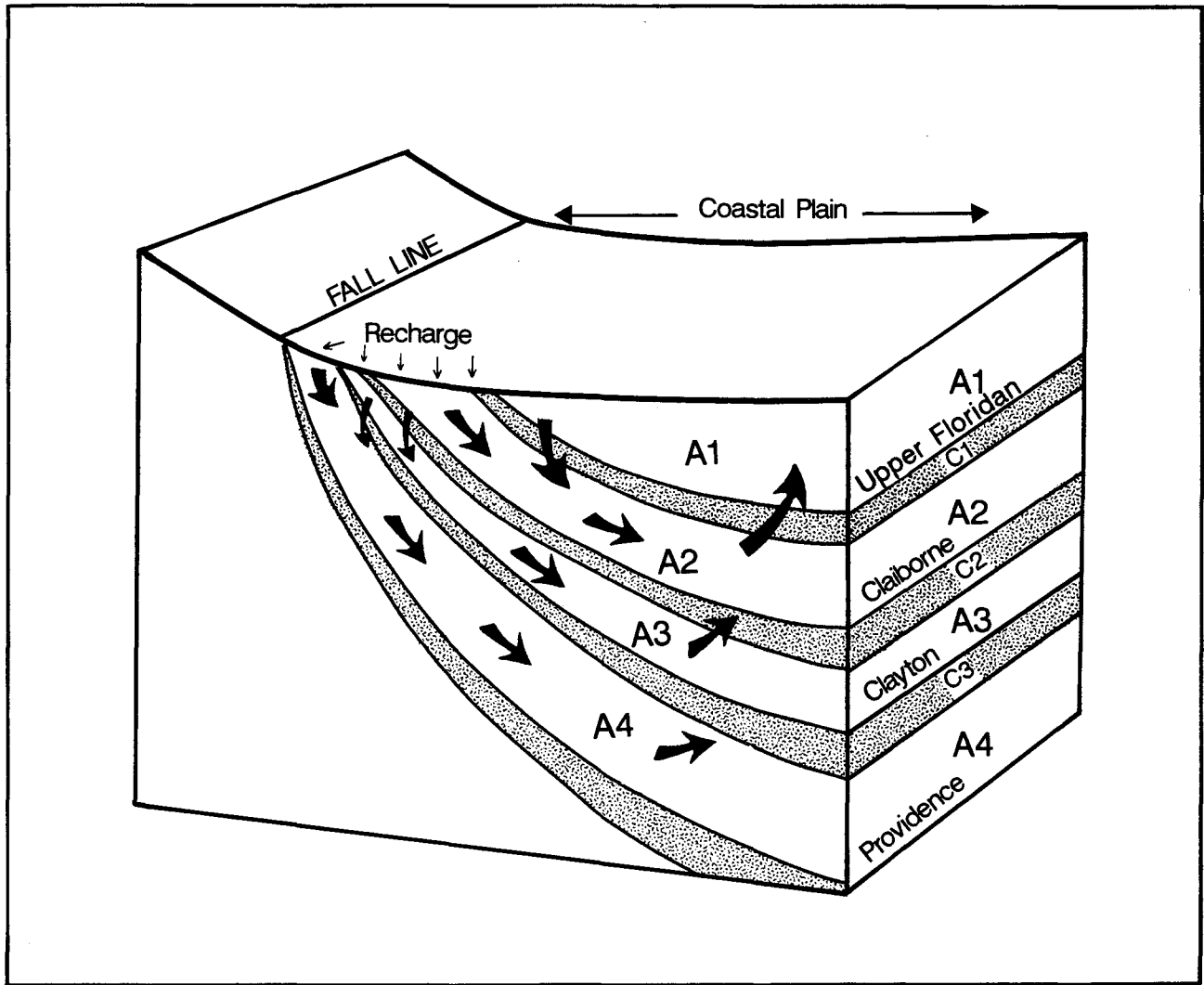
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Figure 1. Study Area.

Figure 2. Schematic diagram of regional ground-water flow in the Upper Floridan (A1), Claiborne (A2), Clayton (A3), and Providence (A4) aquifers. Semiconfining units or units of lower hydraulic conductivity are C1, C2, and C3. Dark arrows indicate direction of ground-water flow.
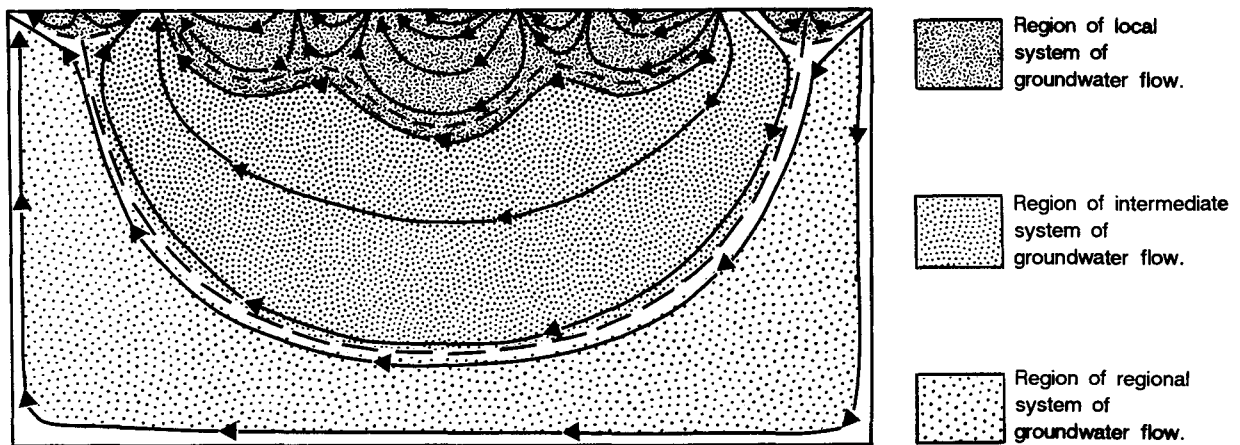

Figure 3. Local, intermediate, and regional ground-water flow (modified from Toth, 1963).

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SYSTEM	EPOCH/SERIES	GEOLOGIC FORMATIONS			HYDROLOGIC FORMATIONS	MODEL LAYERS
TERTIARY	Oligocene	N/A			N/A	N/A
	Eocene	Ocala Limestone			Upper Floridan Aquifer	A1
					Floridan-Claiborne Confining Unit	C1
		Claiborne Group	Lisbon Formation		Claiborne Aquifer	A2
			Tallahatta Formation			
		Wilcox Group	Hatchetigbee Formation		Claiborne-Clayton Confining Unit	C2
			Tuscahoma Formation			
			Nanafalia Formation			
	Paleocene	Clayton Formation			Clayton Aquifer	A3
					Clayton-Providence Confining Unit	C3
CRETACEOUS	Gulfian	Providence Sand			Providence Aquifer	A4
		Ripley Formation			Providence Confining Unit	N/A

Figure 4. Stratigraphic column, hydrogeologic units, and model layers.

16
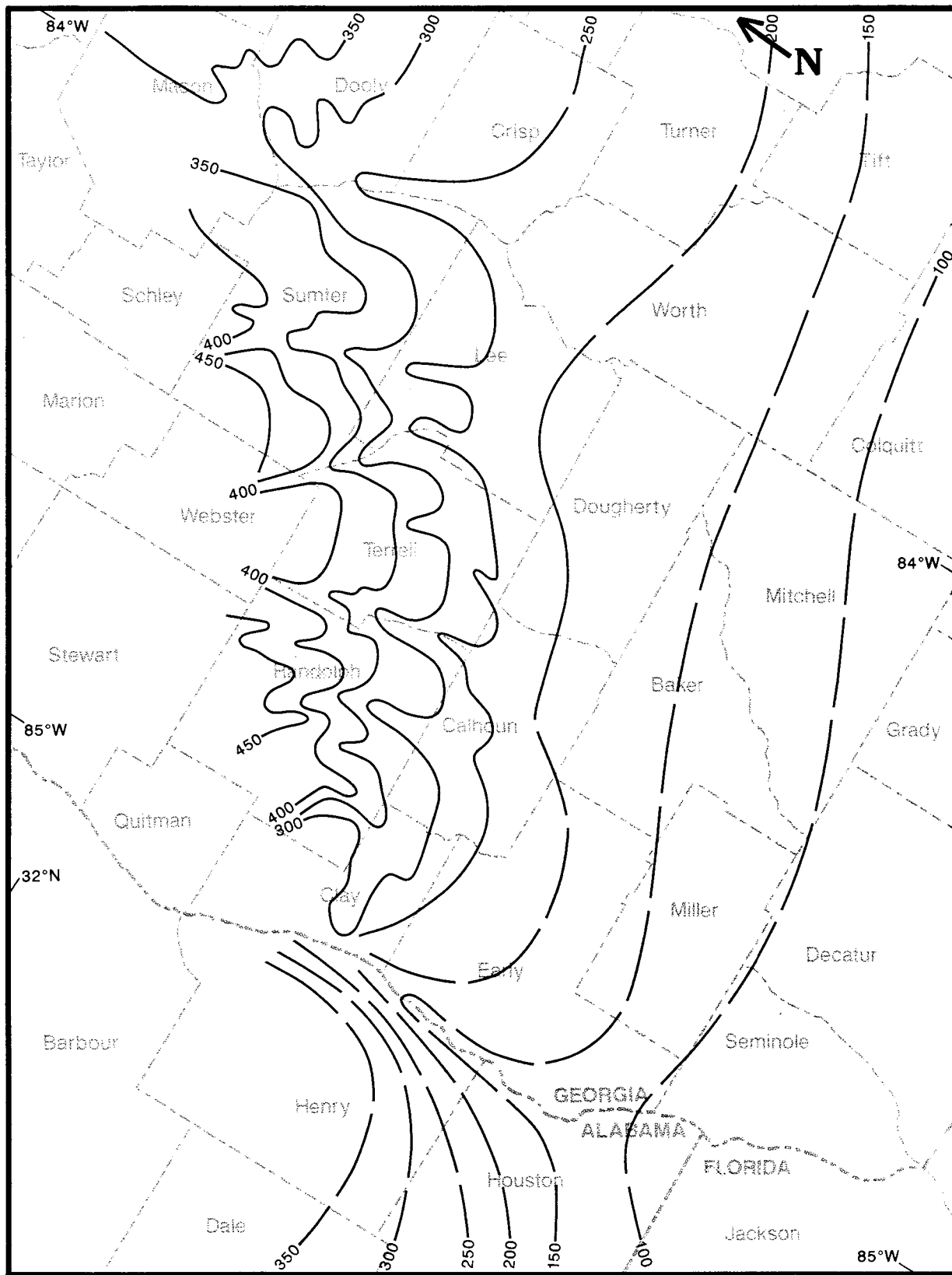
Figure 5. Predevelopment potentiometric surface of the Claiborne aquifer.

17

84°W

Macon   Dooly

N

250

Taylor   Crisp   Turner

Tift 200

300

350 Schley Sumter Worth

450

400

450 Lee 150

Marion 400 Colquitt

350 Webster Dougherty 84°W

450 Terrell

400 Mitchell

350

Stewart 300 Randolph Baker Grady

85°W Calhoun

250

Quitman

32°N Clay Miller Decatur

200 250 300 Early Seminole

400 350

450 Barbour GEORGIA

ALABAMA FLORIDA

Henry Houston Jackson

Dale 250 200 150 85°W

350
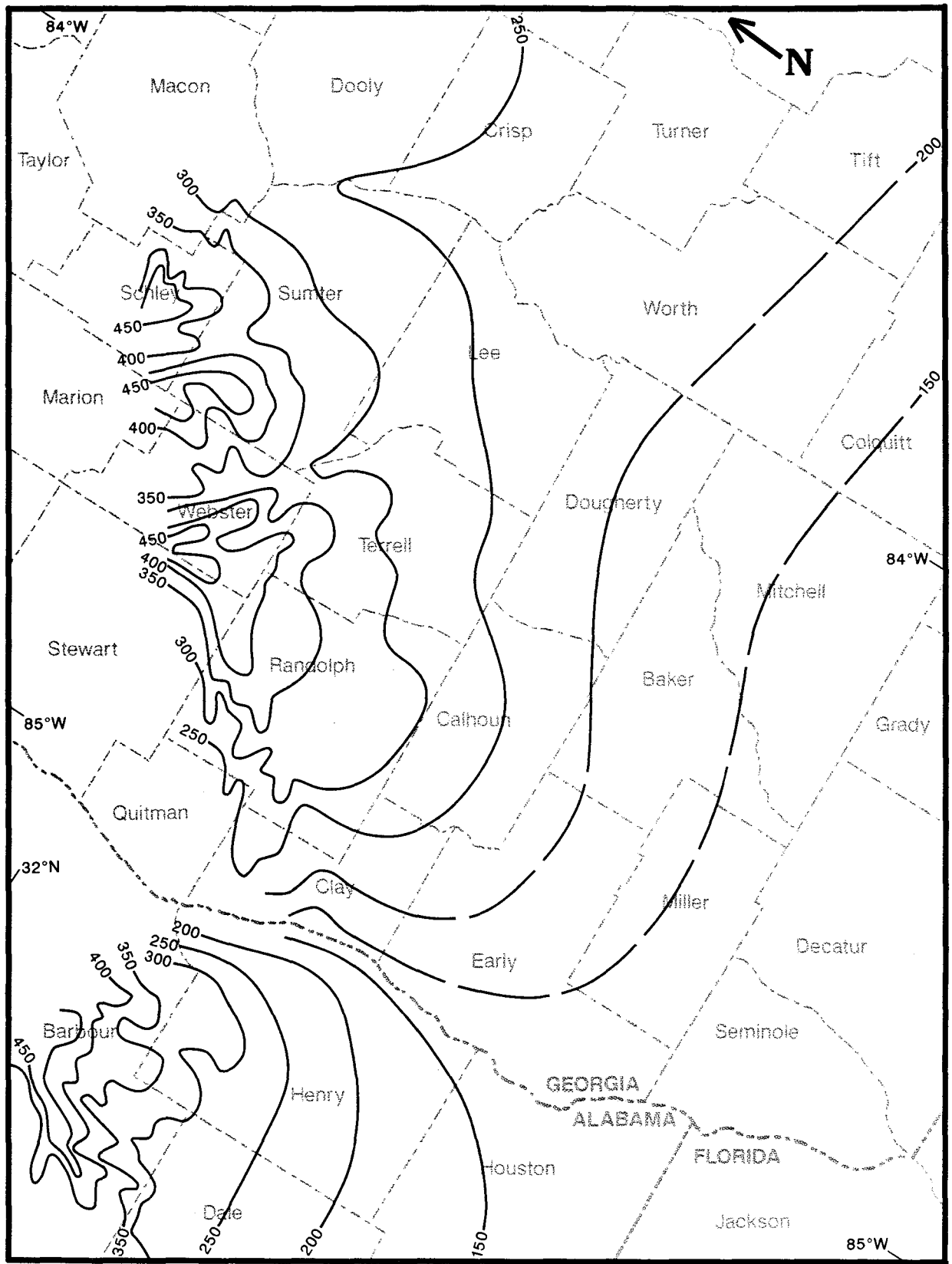
0   10   20   30   40 miles

———200———Elevation of potentiometric surface in feet above mean sea level.

Figure 6. Predevelopment potentiometric surface of the Clayton aquifer.
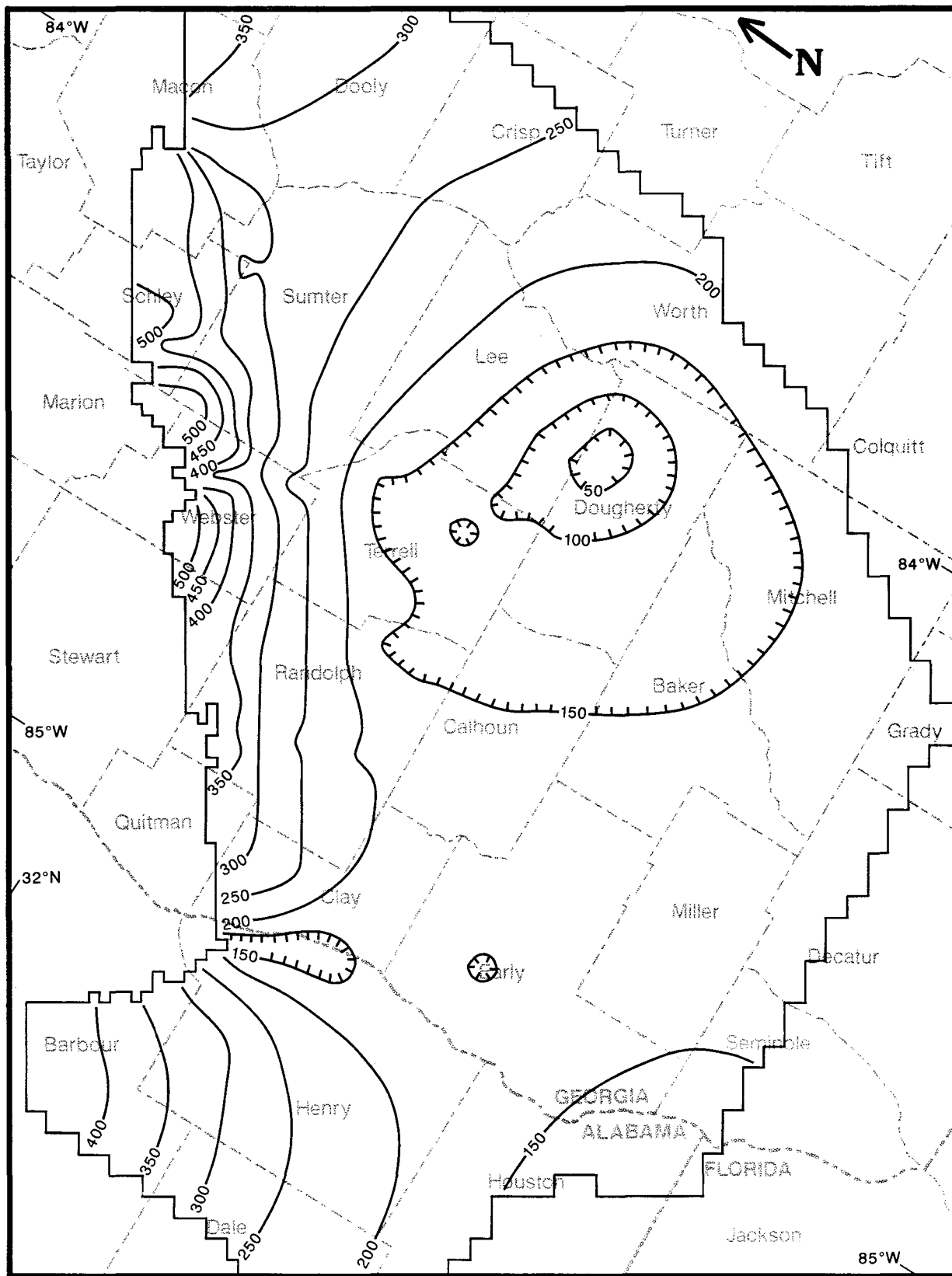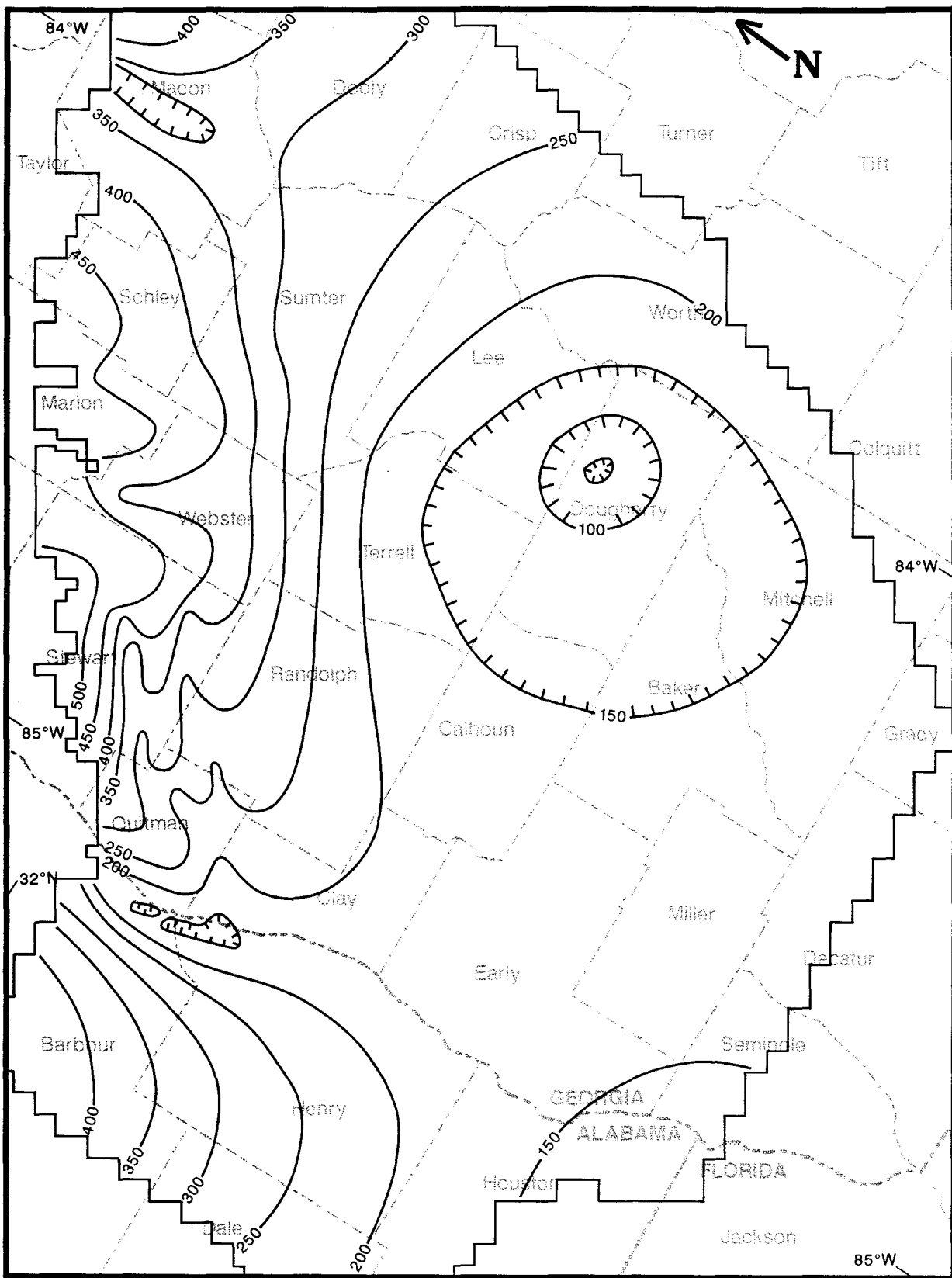
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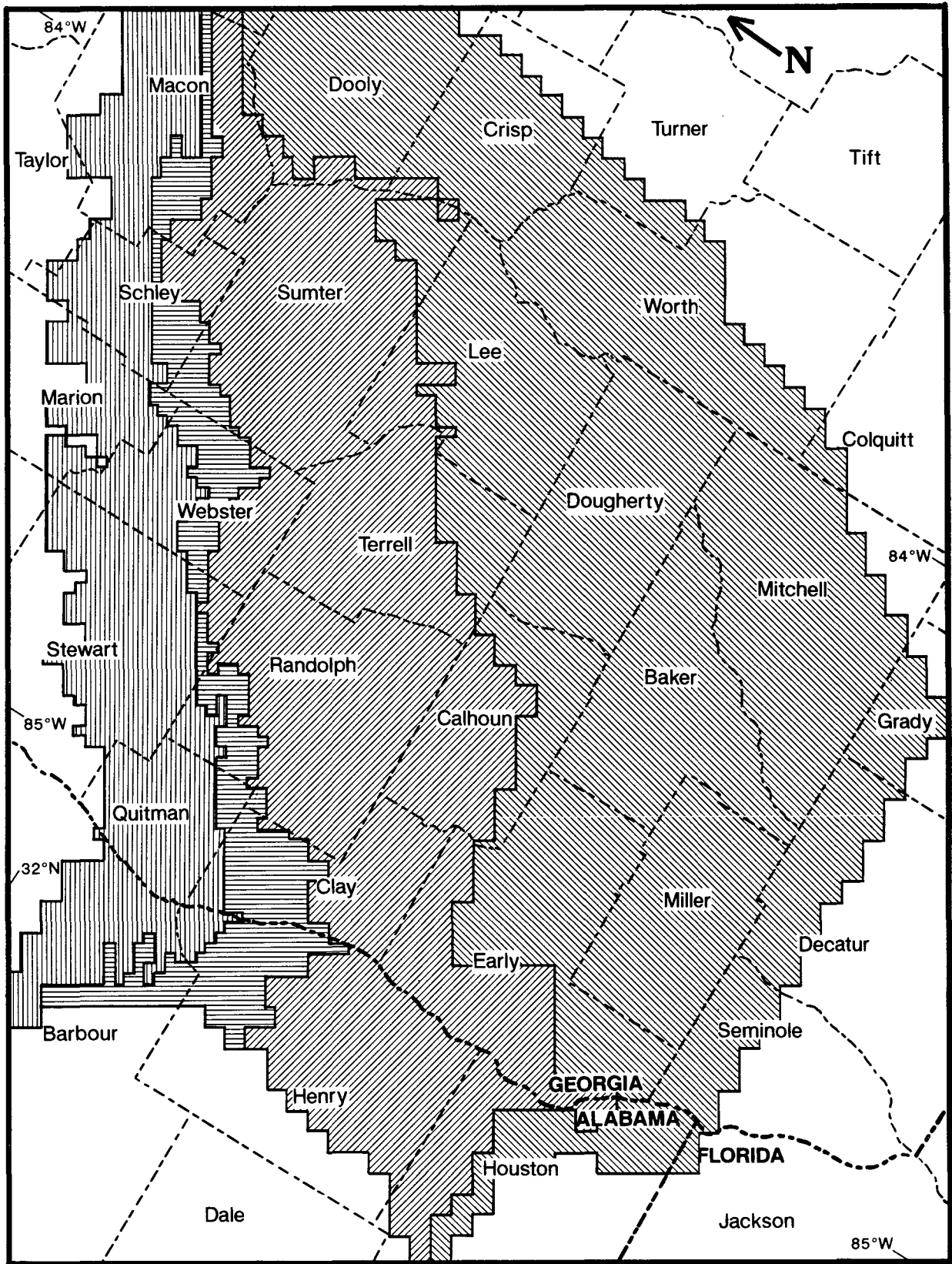
Figure 7. Finite-difference boundary conditions.

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Figure 8. Simulated potentiometric surface in model layer A2 at the end of the five-year baseline simulation.

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Elevation of potentiometric surface in feet above **mean sea level**.

Figure 9. Simulated potentiometric surface in model layer A3 at the end of the five-year baseline simulation.
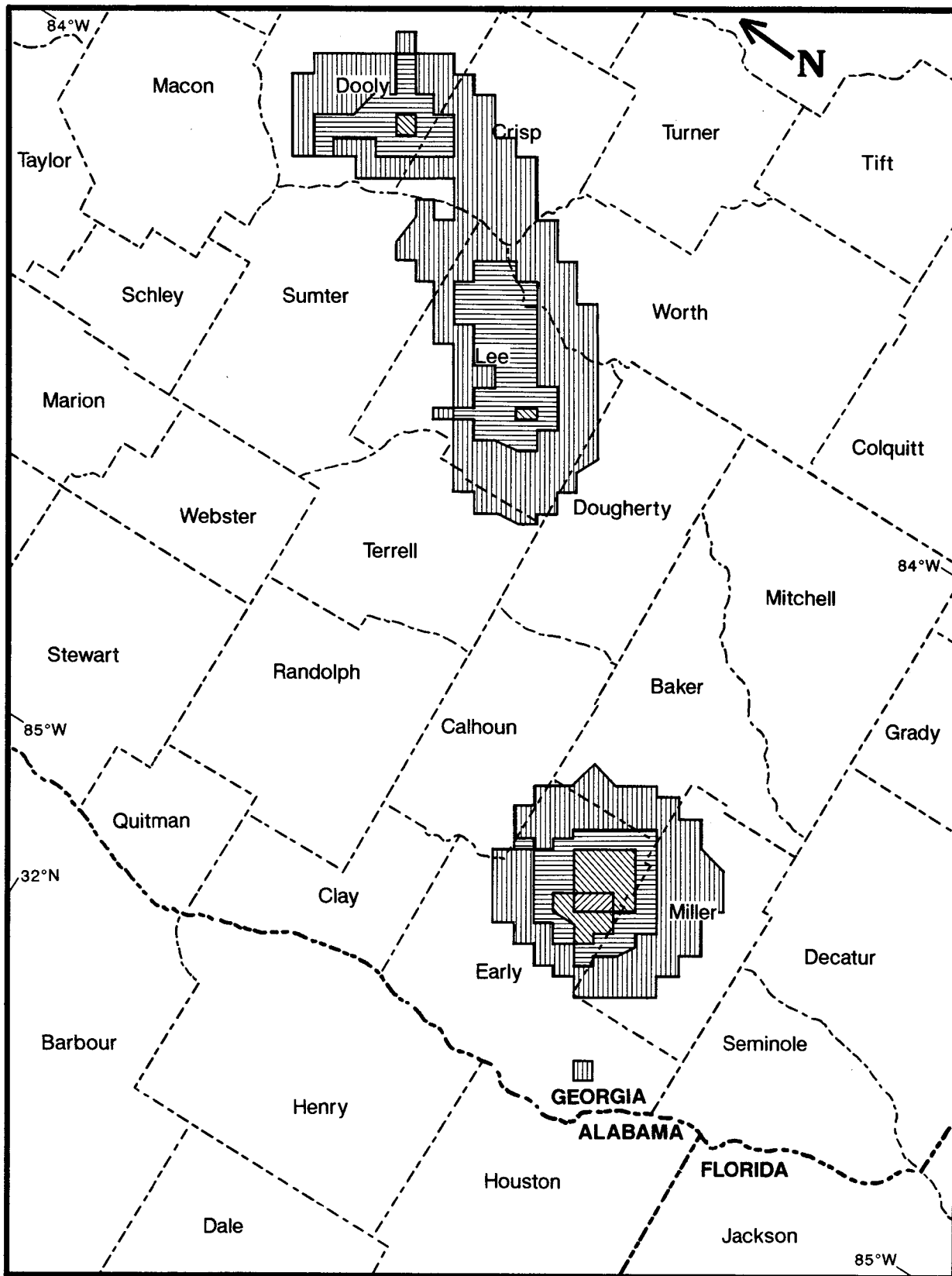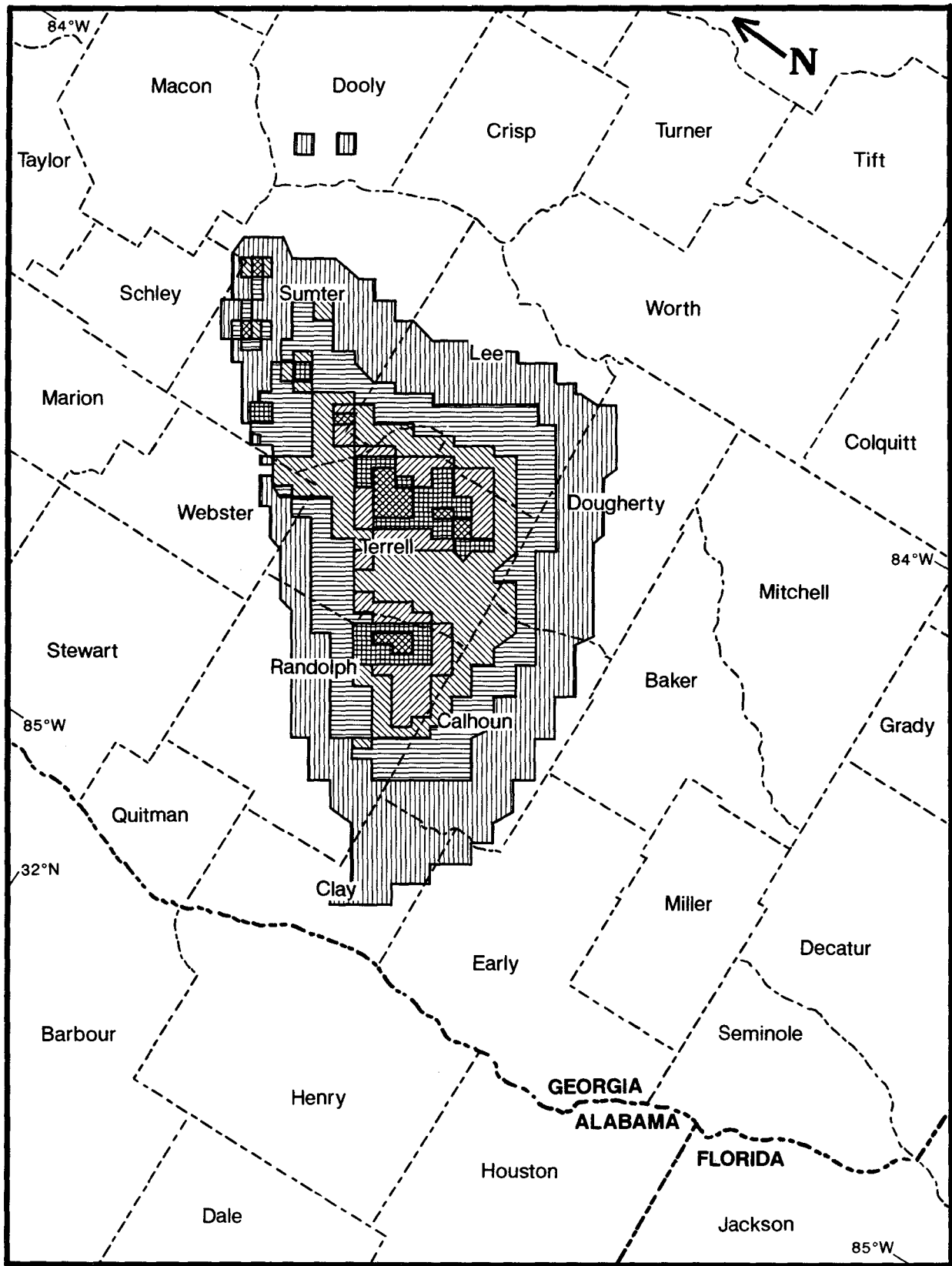
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Figure 10. Simulated potentiometric surface in model layer A4 at the end of the five-year baseline simulation.

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Figure 11. Change in simulated head in model layer A2 in response to a hypothetical two-year drought.

Figure 12. Change in simulated head in model layer A3 in response to a hypothetical two-year drought.
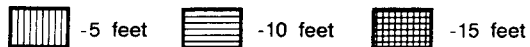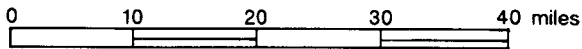
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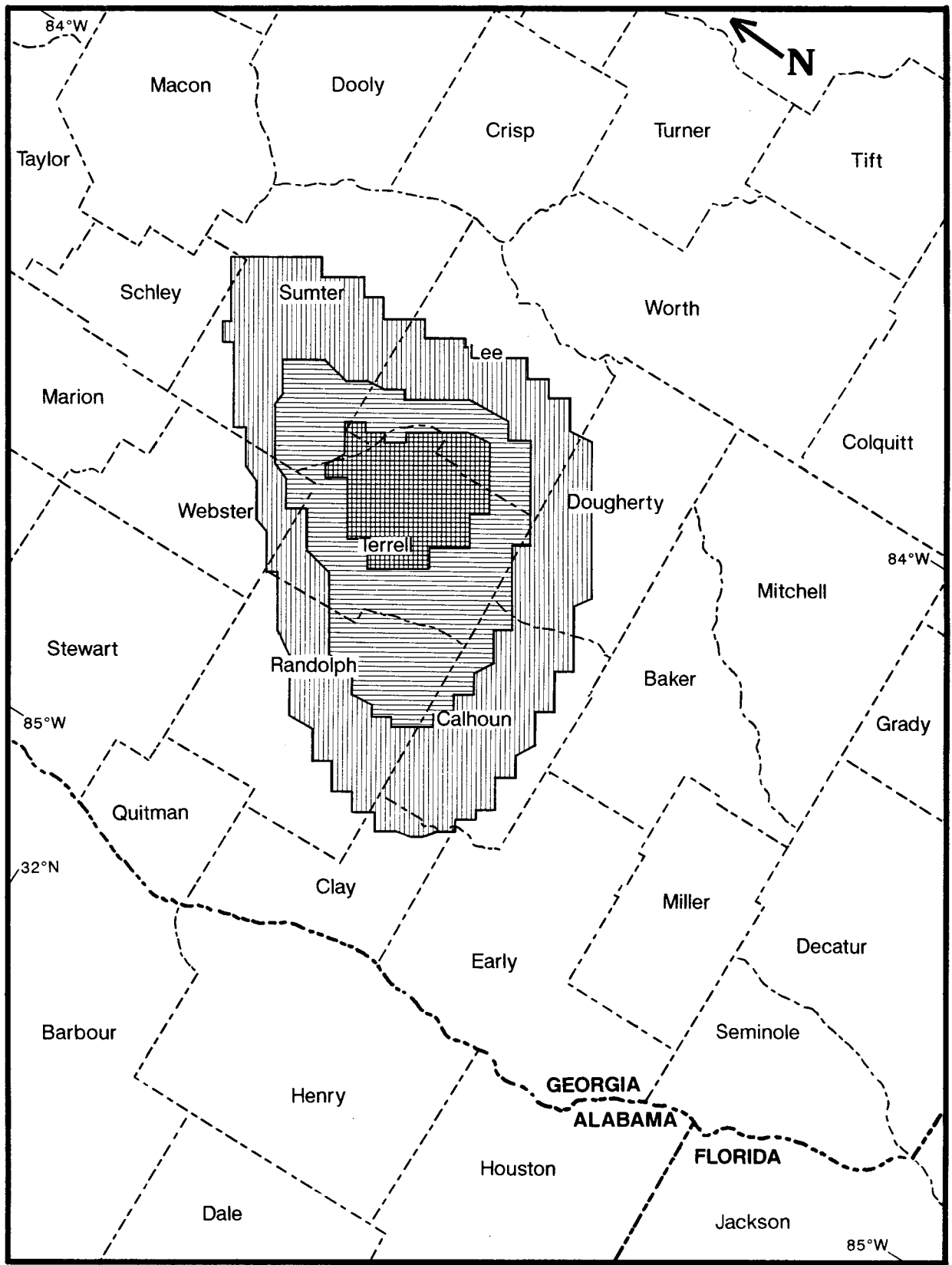**Figure 13.** Change in simulated head in model layer A4 in response to a hypothetical two-year drought.

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Figure 14. Change in simulated head in model layer A2 due to a simulated withdrawal of one million gallons per day from both layers A2 and A3.
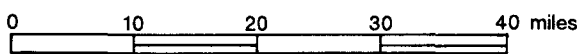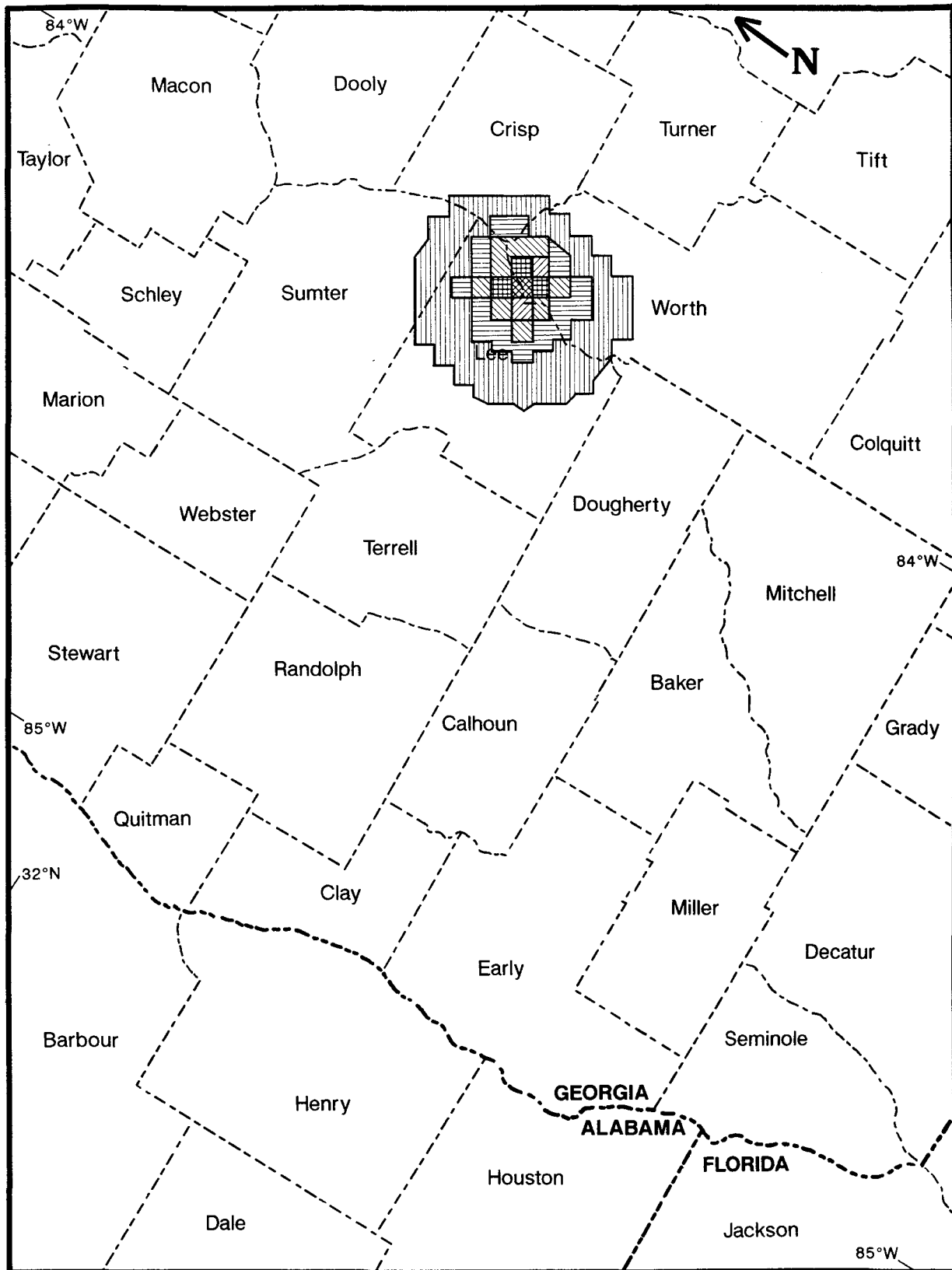
Figure 15. Change in simulated head in model layer A3 due to a simulated withdrawal of one million gallons per day from both layers A2 and A3.
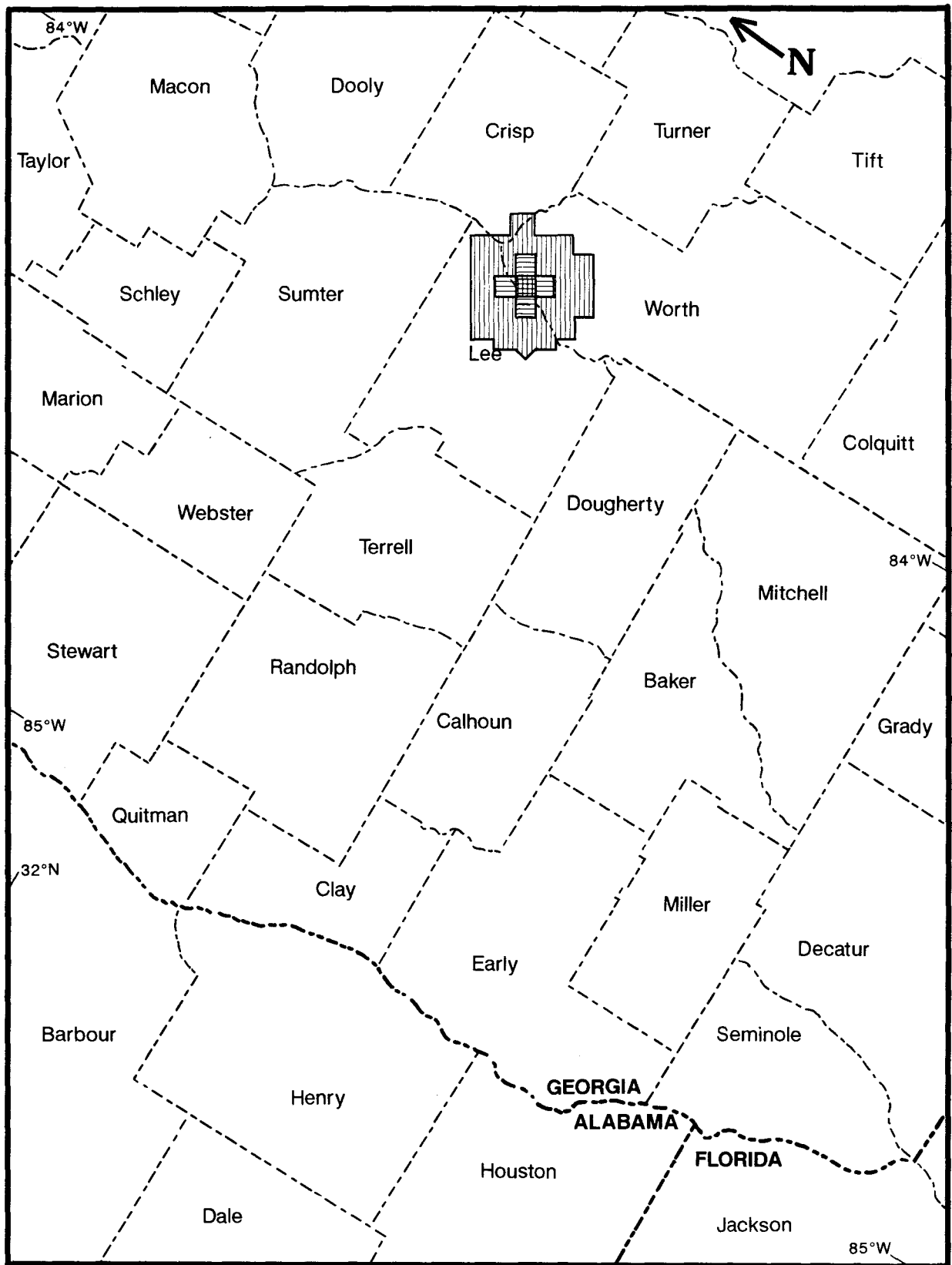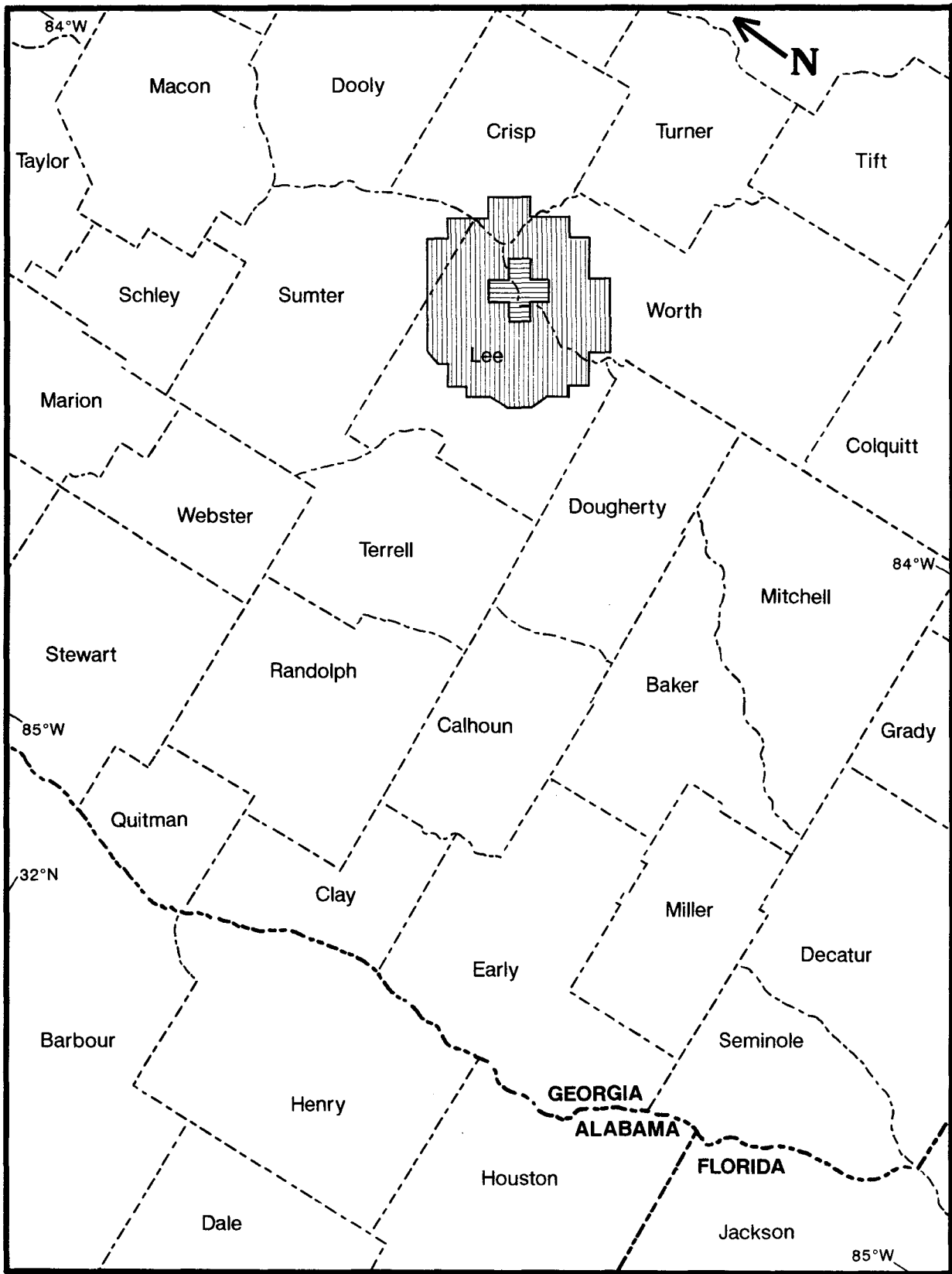
Figure 16. Change in simulated head in model layer A4 due to a simulated withdrawal of one million gallons per day from both layers A2 and A3.
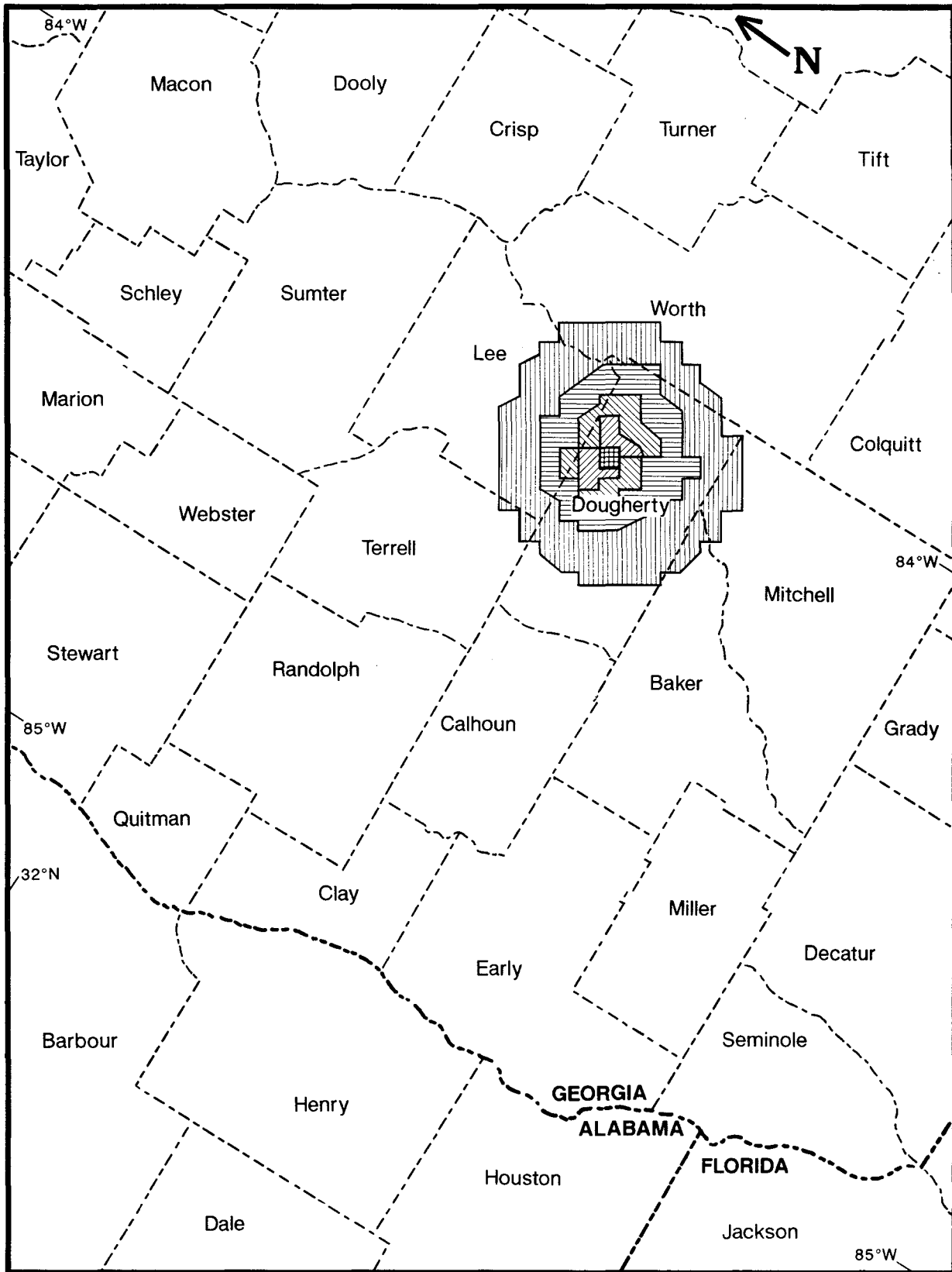
Figure 17. Change in simulated head in model layer A2 due to a 20 percent reduction in pumping from the Claiborne, Clayton, and Providence aquifers for the City of Albany.

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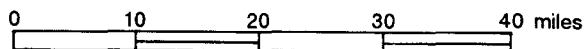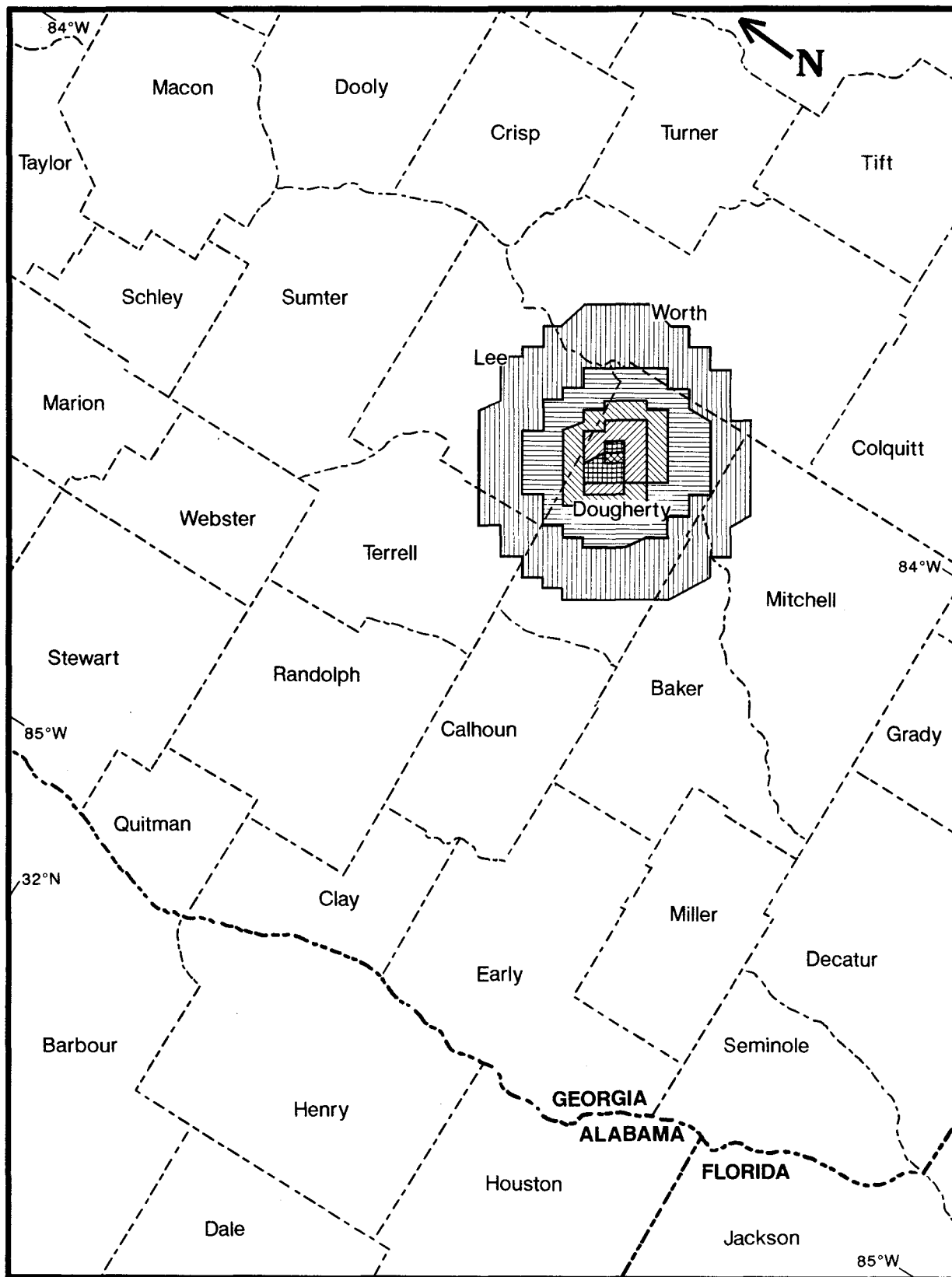
Figure 18. Change in simulated head in model layer A3 due to a 20 percent reduction in pumping from the Claiborne, Clayton, and Providence aquifers for the City of Albany.

Figure 19. Change in simulated head in model layer A4 due to a 20 percent reduction in pumping from the Claiborne, Clayton, and Providence aquifers for the City of Albany.

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APPENDIX A: BASEFLOW ANALYSIS

Streamflow data for the Chattahoochee River allow estimation of ground-water discharge from the combined Providence and Clayton aquifers, and from the Claiborne aquifer.

Gaging station 02342960 at Eufala, Alabama is located very near the northern edge of the Providence aquifer outcrop area. Daily mean discharge at this station on October 5, 1954 was 877 cfs. Downs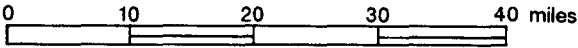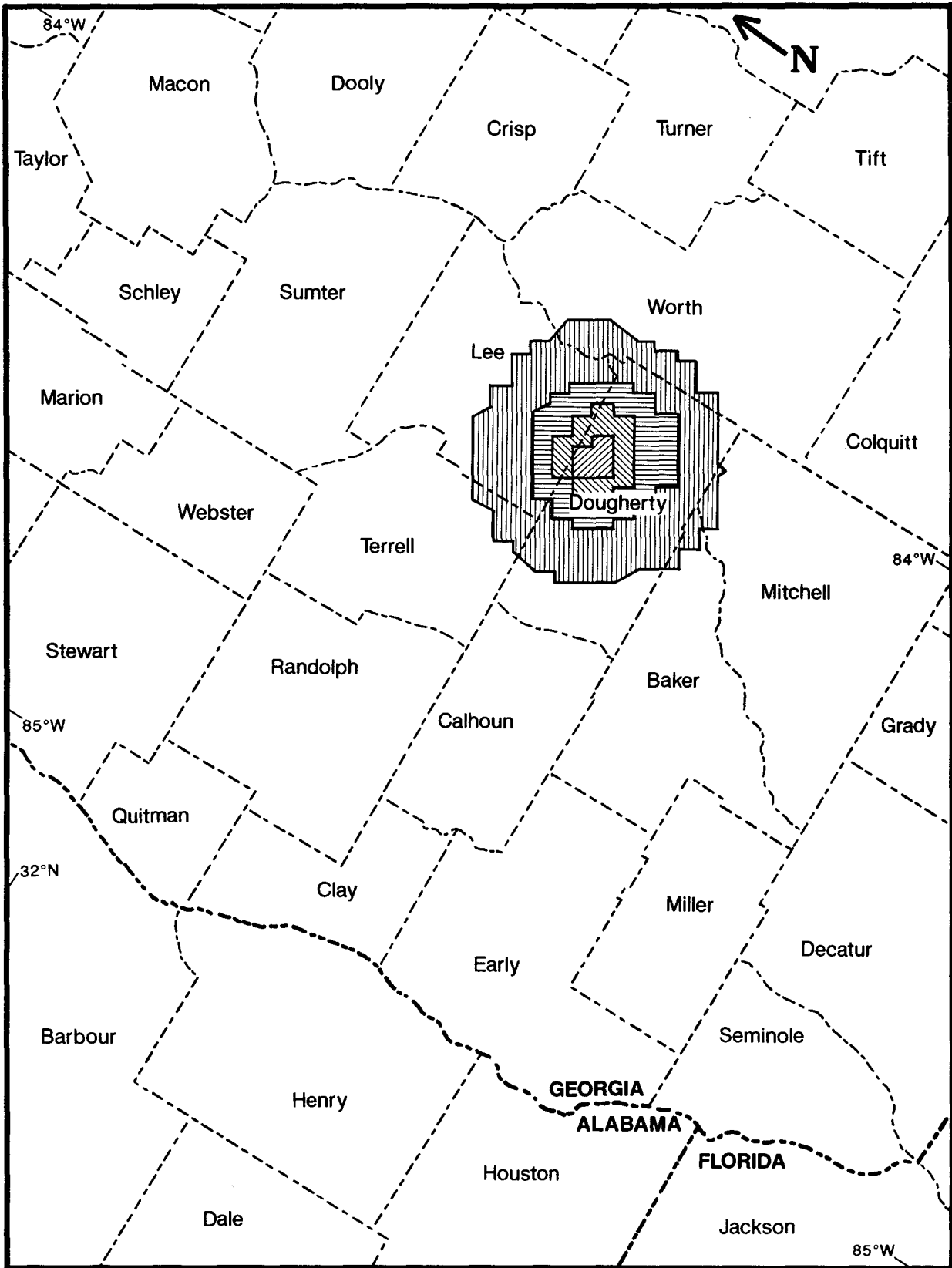tream, at Fort Gaines, daily mean discharge at station 02343260 on October 5, 1954 was 1,120 cfs. This station is located approximately at the southern edge of the outcrop of the Clayton aquifer. Daily mean discharge was used because minimum mean monthly streamflow was not available for these stations. Comparison with upstream and downstream stations that have daily and minimum mean monthly values indicates that the flow on October 5, 1954 approximates the minimum mean monthly flow. The reach delimited by these two gaging stations approximates the recharge area of the combined Providence and Clayton aquifers.

The respective tributary streamflow into the Chattahoochee, however, must be subtracted to estimate baseflow discharge into the River. Streamflow was measured and minimum monthly streamflow computed for the Tobanee, Pataula, Holanna, and Cemochechobee Creeks in Georgia. Stream flow from the unmeasured lower reach of Pataula Creek as well as Barbour, Cheneyhatchee, and White Oaks Creeks in Alabama was estimated using the drainage area-ratio method using the Pataula Creek partial record station data. Addition of tributary streamflow and application of probable error produces a range of streamflow of 187-247 cfs with an average of 217 cfs.

The minimum net gain along the reach of the Chattahoochee River between Eufala and Fort Gaines was calculated by applying the appropriate error and subtracting the maximum values of streamflow from the upstream station, (Chattahoochee River at Eufala [877 cfs x 1.05 cfs = 921 cfs]) and tributary streamflow (247 cfs) from the minimum value of streamflow for the downstream station (Chattahoochee River at Fort Gaines [1,120 x 0.95=1,064 cfs]). This yielded a minimum net gain of -104 cfs (1,064-247-921), which is interpreted as a minimum value of aquifer discharge from the Providence and Clayton aquifers. Average net gain along this reach was calculated by subtracting the value of average streamflow of the upstream station and the tributary streamflow from the average streamflow of the downstream station (1120-217-877). This, in turn, yielded 26 cfs. Maximum net gain was calculated by subtracting the minimum tributary streamflow (187) and minimum upstream streamflow from the maximum downstream streamflow (1176-187-833) yielding 156 cfs.

The headwaters of Ichawaynochaway Creek are in the extreme southeast corner of Stewart County and the southwest corner of Webster County. Ichawaynochaway Creek dissects the Claiborne aquifer outcrop through Randolph and Terrell Counties as it flows to the Flint River in Baker County. Tributaries to Ichawaynochaway Creek are Nochaway Creek and Pachitla and Carter Creeks. Minimum mean monthly streamflow for Nochaway Creek just above the confluence with Ichawaynochaway Creek is reported as 24 cfs (Thomson and Carter, 1963). Minimum mean monthly streamflow for Ichawaynochaway Creek just south of the outcrop downstream of the confluence of Pachitla and Carter Creeks upstream of the confluence with Ichawaynochaway Creek is reported as 51 cfs. The minimum net gain of Ichawaynochaway Creek as aquifer discharge for the Claiborne aquifer was calculated by subtracting the maximum value of Pachitla and Carter Creeks (56 cfs) and the maximum value of Nochaway Creek (24 x 1.10 = 26 cfs) from the minimum value of Ichawaynochaway Creek (140 x 0.90=126 cfs) yielding 44 cfs. Average net gain was calculated by subtracting the mean value of Pachitla and Carter Creeks (51 cfs) and the mean value of Nochaway Creek (24 cfs) from the mean value of streamflow from Ichawaynochaway Creek (140 cfs) yielding 65 cfs. Maximum net gain of Ichawaynochaway Creek as aquifer discharge from the Claiborne aquifer was calculated by subtracting the minimum value of Pachitla and Carter Creeks (51 x 0.90) and the minimum value of Nochaway Creek (24 x 0.90) from the maximum value of Ichawaynochaway Creek (140 x 1.10) yielding 86 cfs.

SUPPLEMENT I: STRATIGRAPHIC AND HYDROGEOLOGIC SETTING

STRATIGRAPHY

General

The Coastal Plain sediments form a seaward thickening wedge of generally unconsolidated units that range in age from Late Cretaceous to early Tertiary (Miller, 1986 and 1990). Successively younger sediments crop out seaward of, and overlie older sediments. Units in the Alabama part of the study area trend along an east-west line and dip to the south. Units in the Georgia part of the study area trend along a northeast-southwest line and dip to the southeast (see Figure I-1). Figure 7 of the text is a generalized stratigraphic column of Upper Cretaceous and Tertiary sediments relevant to this investigation. From oldest to youngest, the lithologic units are described below.

Ripley Formation

The Ripley Formation conformably underlies the Providence Sand. In the study area, the Ripley Formation is a fine-grained marine sand that is generally massive, clayey, calcareous, and highly fossiliferous (Eargle, 1955). The Ripley Formation undergoes a facies change to the east and becomes a clayey coarse-grained sand between the Flint and Ocmulgee Rivers (Clarke, et al, 1983).

Providence Sand

The Upper Cretaceous Providence Sand conformably overlies the Ripley Formation. It consists of medium- to very coarse-grained, cross-bedded sand (Marsalis and Friddell, 1975). The distinctive lower Perote Member of the Providence Sand consists of silt and fine-grained sand (Marsalis and Friddell, 1975). Farther west in Alabama, the upper part of the Providence Sand consists of cross-bedded, fine- to coarse-grained sand and clay with some lignite and kaolin. The basal Perote Member in Alabama consists chiefly of silty clay and very fine to fine-grained sand. The Perote Member thins to the east and is not recognized east of the Flint River (McFadden and Perriello, 1983). Sediments of the Providence Sand become finer grained southward and downdip because they were deposited farther offshore, in the Suwannee Strait (P. Huddlestun, 1991, personal communication).

Clayton Formation

The Clayton Formation unconformably overlies the Providence Sand. The lithology of the Clayton Formation varies considerably over the study area.

Toulmin and LaMoreaux (1963) divided the Clayton Formation into three lithologic units. The lower unit is a basal conglomerate with overlying beds of calcareous sand and sandstone. The middle unit is a coquinoid limestone. The upper unit consists of soft marine limestone. In eastern Alabama, the Clayton Formation consists of a basal sand that is overlain by relatively pure limestone. This limestone is in turn overlain by sandy limestone and sandy clay that comprise the upper part of the formation (Davis, 1987). Very little of the Clayton Formation is exposed at the land surface. The exposed limestone has undergone weathering that has produced a sandy clay residuum. The Clayton Formation was deposited on an irregular surface and later underwent a period of erosion resulting in variable formation thickness (McFadden and Perriello, 1983).

Wilcox Group

The Wilcox Group is composed of three formations: namely: the Nanafalia Formation, the Tuscahoma Formation, and the Hatchetigbee Formation.

The Nanafalia Formation unconformably overlies the Clayton Formation. It is a massively bedded, fine-grained, glauconitic sand and sandy clay. Updip, north of Fort Gaines, the Nanafalia grades into a non-fossiliferous sand with some kaolinitic clay. Downdip, the Nanafalia is a silt and fine-grained sand with some siltstone nodules (Marsalis and Friddell, 1975). In eastern Alabama, the base of the Nanafalia Formation consists of cross-bedded, medium- to coarse-grained sand. The upper and middle parts grade laterally updip into a sequence of interbedded micaceous sand and kaolinitic and carbonaceous clay.

The Tuscahoma Formation overlies the Nanafalia Formation. It has a basal quartz sand that is overlain by thinly bedded silt and clay that is interbedded with fine-grained sands (McFadden and Perriello, 1983). The basal part is more calcareous downdip. The Tuscahoma Formation does not change lithologically to the east in the study area and is readily distinguished from other formations (Marsalis and Friddell, 1975). In eastern Alabama, the basal part of the Tuscahoma Formation consists primarily of cross-bedded, medium- to coarse-grained sand. The upper part consists of silty clay.

The Hatchetigbee Formation consists of sand and marl. It conformably overlies the Tuscahoma Formation. The marl is discontinuous and is interbedded with massively bedded sand. In eastern Alabama the updip part of the

Hatchetigbee Formation is sand; and the downdip part is the Bashi Marl Member. The Hatchetigbee is less sandy in Alabama and resembles the Tuscahoma lithologically. It is difficult to separate the Hatchetigbee from the Tuscahoma except where it interfingers with the Bashi Marl.

As a general rule, the Wilcox Group sediments thicken and become finer grained southward toward the Suwannee Channel axis (P. Huddlestun, 1991, personal communication, unpublished structure contour and isopach maps).

Claiborne Group

In the study area, the Claiborne Group is made up of the Tallahatta Formation and the Lisbon Formation.

The Tallahatta Formation typically is a massive, quartz sand having increasing amounts of clay and shell fragments toward the top. The clay content of the Tallahatta increases in the eastern and northern parts of the study area (McFadden and Perriello, 1983). In eastern Alabama, the Tallahatta Formation consists chiefly of sand and sandy clay with beds of 'buhrstone' or massive siliceous siltstone present near the bottom and top of the formation. In northernmost outcrops, the basal part of the Tallahatta is in channels on the upper Hatchetigbee surface. The channel deposits consist of medium to coarse-grained sand that commonly is gravelly and cross-bedded and contains clay clasts at or near the base (Gibson, 1982). Downdip, the base is sandy and less glauconitic than Wilcox deposits. The upper part of the Tallahatta Formation is dominantly fine- to medium-grained sand, but consists of fossiliferous and sandy limestone in many places (Gibson, 1982).

The Lisbon Formation is a dense, brownish-gray marl with thin beds of sandy limestone (McFadden and Perriello, 1983). Near its contact with the Tallahatta it is a calcareous sandstone. In eastern Alabama, the Lisbon Formation consists of fine- to medium-grained, quartzose sand, sandy limestone, and calcareous sandy clay.

In updip areas, the Claiborne Group weathers to a moderately reddish-brown sand, which locally contains light-green waxy clay zones and silicified fossil fragments (Marsalis and Friddel,l 1975). The Claiborne Group generally thickens to the south-southwest, ranging from 50 feet in the northeast to 200 feet in southwest Calhoun and Early Counties. The formations are very similar except that the Tallahatta is more clayey and siliceous, and the Lisbon is more calcareous and fossiliferous (Marsalis and Friddell, 1975).

Ocala Limestone

The Ocala Limestone unconformably overlies the Lisbon Formation in the study area. The Ocala consists of two rock types in most places (Applin and Applin, 1944). The upper part is a fossiliferous limestone; whereas the lower part is a fine-grained and granular, soft to semi-indurated, micritic limestone (Miller, 1986).

The Ocala Limestone outcrop is locally irregular due to the dissolution of limestone. It ranges in thickness from a few feet at the updip limit to about 350 feet in the southeast part of the Dougherty Plain (Hayes, et al, 1983). Its residuum crops out along hilltops and uplands in the southern Fall Line Hills District.

HYDROGEOLOGY

Aquifer Framework

This study is concerned with ground-water flow conditions in a series of interconnected aquifers contained in the wedge of sediments previously described. The aquifers of primary interest are the Claiborne and Clayton aquifers. The Providence and Floridan aquifers were included in the study because of their interconnection with the Claiborne and Clayton aquifers. The relation between these aquifers and stratigraphic units is summarized in Figure 7. The brief descriptions of these aquifers in this report are intended to provide information necessary to understand the conceptual model of the ground-water flow system. A digital ground-water flow model was developed based upon the conceptual model. Detailed descriptions of the aquifers can be found in the references cited.

Upper Floridan Aquifer

The Upper Floridan aquifer is comprised primarily of the Ocala Limestone in the study area. Locally, permeable sands within the underlying Lisbon Formation also are considered part of the Floridan aquifer. The upper surface of the aquifer dips generally to the south and southeast. The outcrop of the Ocala Limestone and its residuum extends from Early County to Dooly County. The Floridan aquifer is simulated in the digital model only as a source/sink layer. Therefore, hydraulic properties of the Floridan aquifer are not relevant to this study. The reader is referred to Miller (1986), Mitchell (1981), Maslia and Hayes (1988), Hicks and others (1987), and Hayes and others (1983) for information on hydraulic properties of the Floridan aquifer in southwest Georgia.

The Floridan aquifer is recharged by infiltrating rainfall and by vertical leakage from its

overlying residuum and from the underlying Claiborne aquifer, where head differences and the leakance of the confining unit permit. The Floridan aquifer discharges to streams that incise the aquifer and to adjacent aquifers by vertical leakage.

Claiborne Aquifer

The Tallahatta Formation is the main component of the Claiborne aquifer. Sands at the base of the overlying Lisbon Formation and at the top of the underlying Hatchetigbee Formation are locally present and are included as a part of the Claiborne aquifer. Clay layers of the Lisbon Formation separate the Claiborne aquifer from the overlying Floridan aquifer. The Hatchetigbee and Nanafalia Formations contain clay layers that separate the aquifer from the underlying Clayton aquifer (McFadden and Perriello, 1983; Long, 1989).

Sediments that comprise the Claiborne aquifer crop out in a band extending from northern Early and southern Clay Counties northeastward to southern Macon and northern Dooly Counties (McFadden and Perriello, 1983). The Claiborne aquifer thickens toward the south and southeast. McFadden and Perriello (1983) suggest that the thickness and lithology of the sediments that comprise the Claiborne aquifer are relatively uniform. The sediments of the Claiborne aquifer become siltier in the vicinity of Decatur, Mitchell, and Worth Counties (P. Huddlestun, 1995, personal communication). South of this area, these sediments are not considered to be a viable aquifer. Reported values of transmissivity range from 700 to 14,000 feet squared per day (ft²/d) (McFadden and Perriello, 1983). Many of the reported transmissivity values are based on specific capacity and should be considered as estimates only. The storativity of the Claiborne aquifer has been reported at only two locations in the study area, both near Albany. McFadden and Perriello (1983) report that the storativity at the two sites ranged between 0.001 and 0.0003.

The primary source of recharge to the Claiborne aquifer is infiltration of precipitation where the sediments that comprise the aquifer crop out. Exclusive of the Floridan, the area of outcrop of the Claiborne Group is the broadest of the aquifers being studied. McFadden and Perriello (1983) estimate that the area of Claiborne outcrop receiving recharge is approximately 350 square miles. The leakance of the confining unit between the Floridan and Claiborne aquifers permits leakage of water to be an important source of recharge and discharge to the Claiborne aquifer

where heads are sufficiently different in the two aquifers. Head relations between the Claiborne aquifer and the underlying Clayton aquifer are such that it is unlikely that the Claiborne aquifer receives significant leakage from the Clayton.

Much of the water that recharges the Claiborne aquifer discharges to streams and rivers that dissect the area in which it crops out. The aquifer outcrop is incised by a number of creeks and rivers including the Chattahoochee and Flint Rivers and Kinchafoonee, Muckalee, Ichawaynochaway, Nochaway, Pachitla, and Carter Creeks. Smaller creeks and tributary streams also receive discharge from the Claiborne aquifer. Downdip, the Claiborne aquifer discharges water by vertical leakage to other aquifers, and by pumpage of wells.

Clayton Aquifer

The Clayton aquifer is composed mainly of limestone from the middle part of the Clayton Formation. Sands in the upper and lower parts of the Clayton Formation are locally present in hydraulic continuity with the limestone, and are included in the aquifer. Clay units within the upper part of the Clayton Formation and the Hatchetigbee and Nanafalia Formations separate the Clayton aquifer from the overlying Claiborne aquifer. Silts and clays in the lower part of the Clayton Formation and the upper part of the Providence Sand separate the Clayton and Providence aquifers at most locations.

The outcrop of the sediments that comprise the Clayton aquifer stretches from southern Quitman and northern Clay Counties, eastward into west-central Macon County (McFadden and Perriello, 1983). The outcrop area is broadest in the west and is quite restricted in the east. The Clayton aquifer dips toward the south and southeast. The aquifer generally thickens to the south and southwest. The Clayton aquifer thins considerably east of the Flint River. The upper and lower contacts of the Clayton Formation are erosional in nature, therefore the thickness may vary considerably over relatively short distances (McFadden and Perriello, 1983). A facies change resulting in the silting and thinning of the sediments comprising the Clayton aquifer occurs along a line from southern Early County, across northern Miller County and into Mitchell County. This facies change occurs at the southern extent of both the Clayton aquifer and the Clayton Formation (P. Huddlestun, 1995, unpublished isopach and structure-contour maps). Reported transmissivity values for the Clayton aquifer range from 300 to 13,000 ft²/d (McFadden and Perriello

1983). Many of the reported transmissivity values are based on specific capacity, and should only be considered as estimates. The broad range in transmissivity of the Clayton aquifer is attributed to wide variation in the aquifer thickness due to the erosional nature of both the top and bottom of the aquifer. Calculated values of the storativity of the Clayton aquifer are very sparse, but range from 0.003 to 0.00003 (Stewart, 1973; McFadden and Perriello, 1983).

Rainfall infiltrating the Clayton Formation outcrop area and vertical leakage from other aquifers recharge the Clayton aquifer. Rainfall infiltration to the Clayton aquifer is limited due to the aquifer's small outcrop area (estimated by McFadden and Perriello (1983) to be approximately 75 square miles), relatively low permeability of weathered Clayton Formation residuum, and steeper slope in the outcrop area relative to the other aquifers in the study. These factors combine to result in most of the rainfall running-off or evapotranspiring rather than percolating downward (McFadden and Perriello, 1983). The leakance of the confining units above and below the Clayton aquifer is large enough to allow vertical leakage into the aquifer from the overlying Claiborne aquifer and the underlying Providence aquifer, given a significant head difference between the aquifers. The vertical movement of water into the Clayton aquifer is an important source of water in areas where the Clayton aquifer is more heavily pumped.

Water from the Clayton aquifer discharges to streams and rivers that cross the outcrop of the sediments that comprise the aquifer. The aquifer discharges water as vertical leakage to the overlying Claiborne aquifer, and to the underlying Providence aquifer where the head in the Clayton is greater than the head in the adjoining aquifer. Use of the Clayton aquifer for water for irrigation, public supply and industrial uses has resulted in pumpage being the most significant form of aquifer discharge.

Providence Aquifer

Sand units in the Providence Sand comprise the Providence aquifer. Overlying clays and silts within the lower part of the Clayton Formation and the uppermost part of the Providence Sand separate the aquifer from the overlying Clayton aquifer. Updip, this confining unit is frequently absent and the Providence aquifer merges with the Clayton aquifer to locally form the Clayton-Providence aquifer (Clarke, et al, 1983). The Providence aquifer is confined below by silts and fine sands within the lower Perote Member of

the Providence Sand and the Ripley Formation.

The sands that make up the Providence aquifer crop out in a band extending from Quitman County eastward to central and northern Macon County. The Providence aquifer dips to the southeast (Clarke, et al, 1983). Data on the thickness of the Providence aquifer, and other hydraulic parameters, are sparse. The greatest reported thicknesses within the area of this study are in western Dougherty County and southern Crisp County (Clarke, et al, 1983). The down-dip part of the Providence Sand becomes silty along a line extending from southern Early County, through northern Miller County and toward southern Worth County (Applin and Applin, 1944; P. Huddlestun, 1995, personal communication). South of this area, the Providence Sand is not considered to be a viable aquifer. Clarke and others (1983) report transmissivity values ranging from 800 to 4,600 ft²/d for wells that are screened in the Providence aquifer. Many of the reported transmissivity values were based on specific capacity and should be considered as estimates only. No estimates of the storativity are available. Studies of the Providence aquifer are hampered by the fact that few wells are constructed strictly in the Providence aquifer.

The primary form of recharge to the Providence aquifer occurs as infiltration of precipitation in the outcrop of the Providence Sand. This is an important source of recharge in much of the outcrop of the Providence aquifer. Much of the water that recharges the Providence is discharged to streams and rivers that cross the outcrop of the Providence Sand. Other forms of discharge from the Providence are vertical flow to overlying or underlying aquifers and flow to wells.

HYDROLOGIC BUDGET

The conceptual model, described previously, qualitatively describes ground-water flow in the study area. Quantitative estimates of various components of the ground-water flow system are helpful in the development of a digital flow model. Stream-flow measurements taken in a period of drought can be used to estimate ground-water flow to streams. As noted earlier in the text, ground-water flow in the intermediate and regional flow systems is the focus of this study. Flow to streams during the drought of 1954 is assumed to be solely from the intermediate and regional flow systems. Data on the discharge to streams from the intermediate and regional flow systems provide a constraint to which the digital model can be calibrated. The stream discharge data are also

useful as a lower limit of recharge to the flow system.

Minimum monthly streamflow at a number of sites for the 1954 drought was estimated by Thomson and Carter (1963). These data were utilized to estimate the discharge of water to streams from intermediate and regional ground-water flow for specific reaches of streams. The measurements upon which the estimates of minimum monthly streamflow are based generally do not coincide with the updip or downdip limits of the outcrop of the units comprising a specific aquifer (see Figure I-1 for locations). There are a number of possible errors associated with the estimated minimum monthly flows and the discharge measurements upon which they are based (Thompson and Carter, 1963). However, for the basis of this analysis, the error associated with partial record stations (including all of the reaches in this analysis with the exceptions of those on the Flint and Chattahoochee Rivers) is assumed to be plus or minus 5 percent. Minimum monthly flows from continuous record stations are assumed to have an error of plus or minus five percent. Errors for estimates of monthly minimum flow based on basin drainage area are assumed to be plus or minus 10 percent. Minimum monthly flow rates estimated from drainage area comparisons were used for several tributaries to the Chattahoochee River, and for the reach of Pataula Creek between station number 788 and the Chattahoochee River (see Figure I-1).

The ground-water flow to Kinchafoonee Creek from the Providence aquifer was calculated by taking the minimum monthly flow at Preston, Georgia, at the southern margin of the Providence aquifer outcrop (Thomson and Carter map number 886, 40 cfs [1963]) and subtracting the minimum monthly flow at the upper margin of the Providence aquifer outcrop, southwest of Buena Vista (map number 885, not shown on Figure I-1, 12 cfs) and the contribution of Slaughter Creek (map number 885A, 6.5 cfs). This results in an estimated discharge of 21.5 cfs from the intermediate and regional ground-water flow systems of the Providence aquifer. Application of the appropriate errors indicates that the discharge could be as great as 27.4 cfs (subtracting 90 percent of the upstream and tributary flows from 110 percent of the downstream flow), or as little as 15.7 cfs (subtracting 110 percent of the upstream and tributary flows from 90 percent of the downstream flow). Appendix A lists the estimated ground-water discharge for each stream reach simulated in the digital model along with the maximum and minimum estimates based upon application of potential errors.

Data concerning drought flows in the Flint River and its tributaries were sparse. Most of the estimates of tributary flows were based on drainage areas. Therefore the drought flow estimates for the Flint River have a greater error range than the other values.

The total ground-water discharge to streams from the intermediate and regional flow systems is estimated to be 509 cfs. Although some development of the system of aquifers had occurred at the time of these measurements, it is assumed that the development had little influence on ground-water discharge to streams. These estimates of ground-water discharge to streams were used as a tool in the calibration of the model in the steady-state mode, along with observed heads and boundary fluxes. Under the assumptions of the conceptual model of the flow system, this estimate represents a lower limit of the recharge to the intermediate and regional flow systems. Total recharge to the Claiborne, Clayton, and Providence aquifers will be greater, reflecting the inclusion of local flow systems.
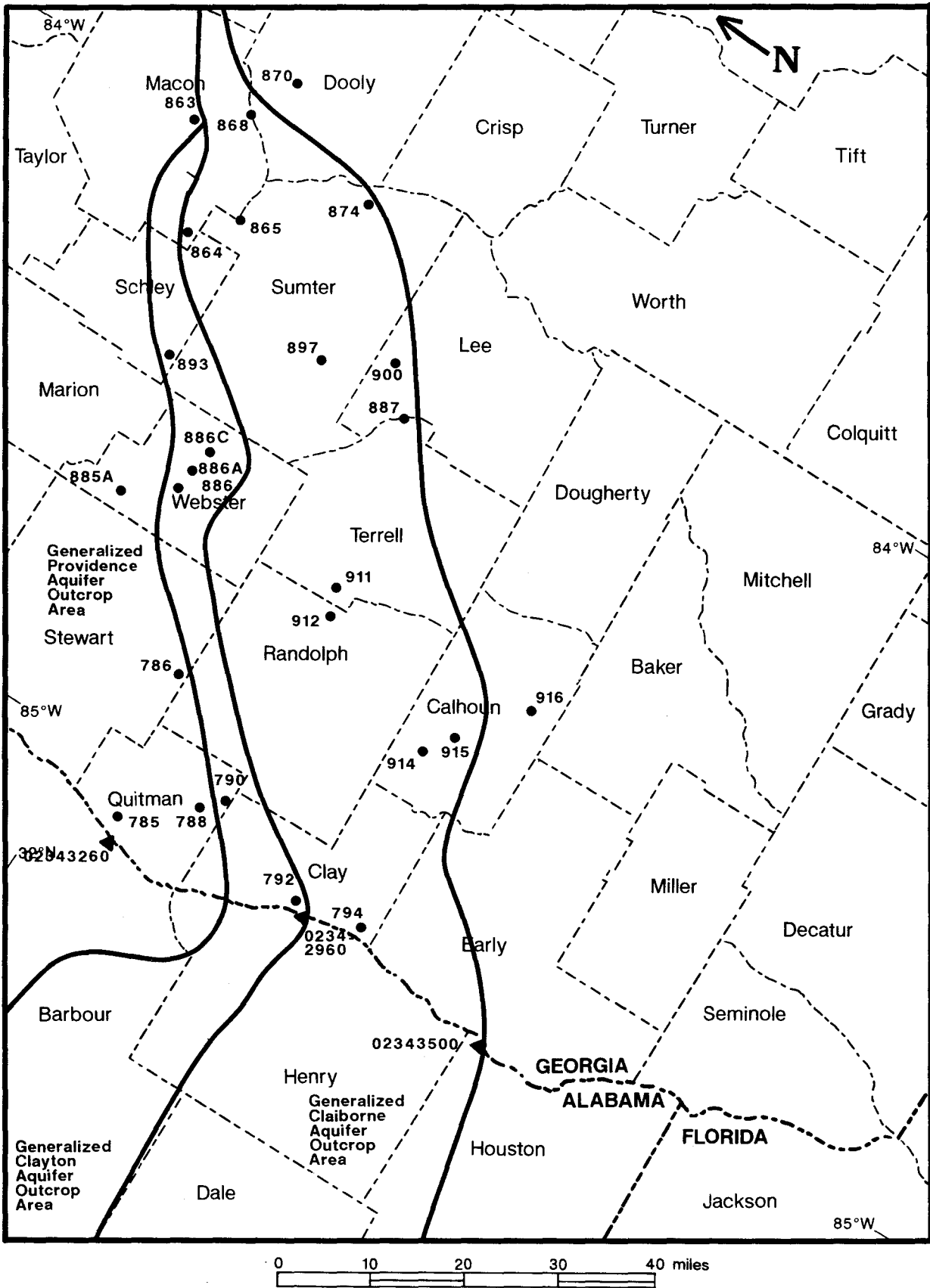
Figure I-1. Streamflow measurement, location, and generalized outcrop areas.

SUPPLEMENT II: DIGITAL MODEL PACKAGE

BOUNDARY CONDITIONS

Layer A1 of the digital model (Figures 2 and 4 of the text) represents the Floridan aquifer. As noted earlier, the Floridan aquifer is included in the model only as a source/sink for the active layers of the model. Therefore heads in all cells where layer A1 is present, shown in Figure II-1, are specified and are held constant. The specified heads are based upon Johnston and others (1980) and Vorhis (1972). The northwestern limit of layer A1 generally corresponds to the up-dip limit of the Ocala Limestone outcrop area as based upon the Geologic Map of Georgia (Georgia Department of Natural Resources, 1976). The western, southern, and eastern boundaries of the grid conform to the boundaries in the active layers.

Active and specified-head cells in layer A2 are shown in Figure II-2. Layer A2 represents the Claiborne aquifer. The dot-patterned area represents those cells for which layer A1 is not present. This generally represents the outcrop area of the sediments that comprise the Claiborne aquifer. The dot-patterned area also includes some areas where the residuum of overlying sediments is thin, and likely to be in hydrologic continuity with the Claiborne aquifer. Where the overlying sediments are included in layer A2, the leakage of water from these sediments is modeled as recharge, rather than leakage. Recharge to layer A2 is applied at a specified rate for each cell within the dot-patterned area.

The northern limit of layer A2 represents the up-dip limit of the outcrop of the sediments that comprise the Claiborne aquifer. The southern limit of layer A2 approximates the down-dip limit of the aquifer, where an increased silt content markedly decreases the transmissivity of the unit. This boundary is simulated as a no-flow boundary. The reduction in the transmissivity of the Claiborne aquifer at the southern extent of the aquifer probably is a gradual reduction in response to increasing silt content, not the sharp decline in transmissivity as indicated by the model. Existing data, however, indicate that the transition zone is relatively narrow (P. Huddlestun, 1995, personal communication). Therefore, this representation is probably adequate for modeling purposes. The eastern boundary of layer A2 represents the predevelopment ground-water divide associated with the interstream divide between the Flint and Ocmulgee Rivers. The location of the boundary is interpreted from several sources of data, including those of McFadden and Perriello (1983) and file data from both the Georgia Geologic Survey and the USGS. The western boundary of layer A2 coincides with the boundary in layers A3 and A4, which are based on ground-water divides. The Claiborne aquifer is affected by intermediate streams that do not influence the Clayton and Providence aquifers. However, given the distance to pumping that is of interest and the intervening Chattahoochee River, the western boundary is believed to be adequate. All four boundaries are simulated as no-flow, where layer A1 is absent; and as a specified-head boundaries, where layer A1 is present as a specified-head cell.

The Clayton aquifer is represented in the digital model by layer A3. Figure II-3 shows the distribution of active and specified-head cells. The brick-patterned area indicates those cells for which layer A2 nodes are inactive, and generally represents the outcrop of the sediments comprising the Clayton aquifer. The active area of layer A3, however, does not include an outlier of Clayton Formation sediments that is present between Hodchodkee and Pataula Creeks in southeastern Stewart, northwestern Randolph and eastern Quitman Counties. Incision of Pataula Creek separates this outlier from the main body of the Clayton aquifer. Water recharging this area is assumed to leak into the underlying Providence aquifer. Therefore, this area is simulated as if it were a part of the Providence aquifer.

The Providence aquifer is represented by layer A4 in the digital model. The extent of layer A4 is shown in Figure II-4. Cells for which only layer A4 is active are diagonal-lined-patterned. These cells represent the outcrop of the sediments that comprise the Providence aquifer and outliers of sediments that would otherwise form a part of the Clayton aquifer. The eastern boundary of layers A3 and A4 approximate the position of the predevelopment ground-water divide between two regional drains, specifically the Flint and Ocmulgee Rivers. The position of these boundaries are based on potentiometric data from McFadden and Perriello (1983), Clarke and others (1983), and file data from both the Georgia Geologic Survey and the USGS. The western boundaries of layers A3 and A4 represent the predevelopment ground-water divide between the influence of the Chattahoochee and Chochtawhatchee Rivers, and is based on file data from the USGS. The eastern and western boundaries of layers A3 and A4 are simulated as specified-head cells where an active or specified-head cell exists in the overlying layer. Where the cell in the overlying layer is not used,

the boundary cell is simulated as an active cell. The McDonald-Harbaugh code permits no flow across the outside faces of exterior cells. The southern boundaries of layers A3 and A4 are in the area where facies changes in the sediments comprising the Clayton and Providence aquifers, result in the aquifers becoming impermeable. As is the case with the southern boundary of layer A2, the southern boundary of layer A4 is modeled as a no-flow boundary rather than the transition to low transmissivity, which is assumed in the conceptual model.

HYDROLOGIC PROPERTIES

Transmissivity

The transmissivity distribution initially used in the digital model was based upon a number of factors including: (1) estimates from time-drawdown data from aquifer tests; (2) from specific capacity data; and (3) the variation in the composition and thickness of the aquifer. As noted in the description of the conceptual model, transmissivity estimates from measured time-drawdown data were virtually non-existent. The lack of transmissivity estimates from time-drawdown data along with the uncertainties that accompany these estimates result in the distribution of transmissivity being known only within a broad range. Therefore, transmissivity is one of the parameters that can be reasonably adjusted in the calibration process.

The distribution of transmissivity for layer A2 used in the calibrated digital model is shown in Figure II-5. Transmissivity derived from aquifer tests and specific capacity for the Claiborne aquifer (McFadden and Perriello, 1983) also are included in Figure II-5. Transmissivities are relatively uniform, reflecting the uniform thickness and lithology of the Claiborne aquifer. The calibrated transmissivity used in the digital model is in general agreement with the reported values, given the uncertainty of the reported transmissivity.

Calibrated transmissivity for layer A3 and reported values from McFadden and Perriello (1983) is shown in Figure II-6. Calibrated transmissivity is, in general, lower than the reported values. Reported transmissivity varies greatly over short distances, as can be noted at Fort Gaines (cells 26-19 and 27-19), Cuthbert (cell 26-34), and at Kolomoki State Park (cell 33-20). Differences as much as 400 percent in relatively closely spaced wells are reported. Figure II-6 does not include transmissivity values that McFadden and Perriello report as anomalous. These anomalous values, however, illustrate the

importance of well construction on estimating transmissivity. Wide variation in transmissivity is expected in the Clayton aquifer due to the variation in aquifer thickness and lithology. There probably is a high bias in the transmissivity estimates because wells penetrating the Clayton aquifer in an area of lower transmissivity are likely to be completed as a multi-aquifer well in order to obtain the desired yield. In addition, it is less likely that a production test will be conducted on a well that produces relatively little water. Relatively low transmissivity used in the calibrated model was required to produce the water-level decline in the area of Terrell County that have been measured, even with pumpage in that area simulated at the upper limits of what was considered reasonable. The low transmissivity used along the eastern and southern part of the digital model reflects the change in character of the sediments that comprise the Clayton aquifer. The higher transmissivity in the western part of the model represents the greater thickness of the aquifer in that area.

The calibrated transmissivity values used in layer A4 of the calibrated model, as well as measured and estimated values reported by Clarke and others (1983) are shown in Figure II-7. The calibrated transmissivity generally is slightly lower than the reported values, but close enough to be within the reasonable error range of the reported values. The high transmissivity of the northern part of layer A4 represents the outcrop region, where the clay content of the Providence aquifer is considered to be lower. The zone of high transmissivity in southwestern Calhoun County is associated with the thickest part of the aquifer. The lower transmissivity in the southern part of layer A4 probably represents the gradual southward fining in grain size of the sediments that comprise the Providence aquifer.

Storage Factor

Storage in the aquifers is represented in the digital model by the storage factor (e.g., storage coefficient). This represents both the unconfined and confined part of the aquifer. In the unconfined part, changes in head result in the draining or saturation of the sediments that comprise the aquifer. Therefore, the storage factor used is the effective porosity. In confined parts, head changes result in yield of water only from expansion or contraction of the water and elastic changes in the aquifer matrix. The parameter used in the confined part of the aquifer is the storativity.

The storage factors of the Claiborne, Clayton, and Providence aquifers are poorly known. The

initial estimates of storativity used in the digital model for layers A2 and A3 are based on the few reported values for the confined section of the layers. The unconfined sections of all three active layers and the confined section of layer A4 are based on generic, empirical estimates. Uniform values for the storage factor were used for all layers due to the lack of knowledge of variations in the storativity and effective porosity. The storage factor was one of the parameters that was adjusted in the calibration process. The effect of changes in the storage factors used in the model were negligible. Therefore, only minor changes in the distribution were made.

The distribution of the storage factor for layers A2, A3, and A4 is shown in Figures II-8, II-9 and II-10, respectively. The northern zone of high storage factor in layers A2, A3 and A4 represents the area of outcrop of the aquifers, and represents the effective porosity of the sediments that comprise the aquifer. Reported storativity of the Claiborne aquifer (McFadden and Perriello, 1983) is included in Figure II-8. The value used in the calibrated model for A2 is within the range of storativity reported by McFadden and Perriello (1983). Storativity reported for the Clayton aquifer by McFadden and Perriello (1983) is indicated on Figure II-9. The storage factor used in the calibrated model for A3 lies within this range of storativity. For the Providence aquifer, no storage factor is estimated.

Leakance

Leakage of water through the confining units is controlled by (1) the head difference between the aquifer units, (2) the vertical hydraulic conductivity of the confining unit, and (3) the thickness of the confining unit. The input to the model is the leakance of the confining unit, defined as the vertical hydraulic conductivity divided by the thickness of the unit. Measured leakance values for the confining units have not been reported. Herrick (1961) described the sediments that comprise the confining unit and the thickness of the unit. From Herrick's description and vertical hydraulic conductivity values were based on Freeze and Cherry's (1979) estimates for a range of lithology were developed.

Calibrated leakance for confining unit C1 is modeled as a single value of $5.8 \times 10^{-12}sec^{-1}$ for the entire area of the confining unit because of the uniform thickness and uniform lithology of the sediments that comprise the confining unit.

Figure II-11 shows calibrated leakance for confining unit C2. Leakance for most of the confining unit ranges from $5.8 \times 10^{-12}sec^{-1}$ to $2.3 \times 10^{-12}sec^{-1}$. The leakance generally decreases toward the southeast as the thickness of the confining unit increases and the vertical hydraulic conductivity decreases. Leakance along the Flint River is higher, reflecting the possibility of the confining unit being partially incised by the river. The leakance, in this area, decreases down river, representing the decreasing effect of the river on the confining unit as it dips down below the river.

Calibrated leakance for confining unit C3 are shown in Figure II-12. Leakance decreases toward the southeast. In the mid-dip area, the decrease represents the thickening of the confining unit. The further decrease, near the southern limit of the model area, represents a decrease in the vertical hydraulic conductivity of the confining unit. Leakance ranges from $1.2 \times 10^{-12}sec^{-1}$ to $5.8 \times 10^{-12}sec^{-1}$.

FLUX CONDITIONS

Recharge

Recharge to the aquifers is simulated in the digital model by use of the recharge module (McDonald and Harbaugh, 1988). The model code multiplies the infiltration rate for each cell (in units of length/time) by the area of the cell to calculate the recharge rate for the cell. Recharge can be applied only to the uppermost active layer, and only to active cells. Estimates of recharge for initial simulations were obtained by first conducting a simulation, in which the cells that would normally receive recharge, were modeled as specified-head cells. In this type of simulation, the model will apply as much flux as is needed to keep the head at the specified level in each cell. The volumetric flux was divided by the cell area to determine the infiltration rates needed for input in the recharge module. These preliminary recharge rates were one of a number of factors that were adjusted in the calibration process. No attempt was made to have the recharge rate vary over time, due to the lack of data upon which to base these changes.

Recharge rates used in the calibrated model range from 0 to 5 1/2 inches/year. Recharge generally was greatest in the interstream divides and lowest in the area of the regional drains.

Rivers

Discharge from the aquifers to rivers is simulated in the digital model by use of the river module (McDonald and Harbaugh, 1988). Flux to or from the river is dependent upon the difference in head between the river and the uppermost

active layer, as well as by a conductance term that incorporates the area of the river, the conductance of the stream bed and the thickness of the stream bed. Input variables to the river module include, for each cell, the river stage, the elevation of the river bottom, and the riverbed conductance term. The average river stage for each cell was estimated from 7.5 minute topographic maps for streams other than the Flint and Chattahoochee Rivers. Estimates of river stage elevations for the Flint and Chattahoochee Rivers were based upon low-stage surveys conducted by the U.S. Corps of Engineers in 1954 (data on file at the USGS). The river-bottom elevations are assumed to be 20 feet below river stage for the Flint and Chattahoochee Rivers. River-bottom elevation for other streams are assumed to be 10 feet below river stage. The river-bed elevation is used in the model only when the flux is from the river to the aquifer, a situation that did not occur in the development of this model. The river-bed conductance was estimated from the area of the river in each cell, based on topographic maps; the thickness of the riverbed, assumed to be five feet for the Flint and Chattahoochee Rivers and three feet for other streams; and an estimate of the hydraulic conductivity of the river bed. The river-bed conductance had to be adjusted during calibration of the model, river stage was not adjusted.

Pumpage

Wells in the area of this study generally are drilled for one of four purposes. The majority of the wells in the study area are used to supply water to individual homes. These domestic wells generally have low yields. The withdrawal from these wells is not considered significant for the purpose of this study. Where homes are concentrated, such as in towns and cities, water is supplied by a public water supply system. The public water systems in the area of this study typically have high-capacity wells. Because these systems are usually operated by a local government, they are termed municipal users. Many industries operate their own high-capacity wells to supply the their needs. The use of water by those industries that buy water from the public supply system is included in the municipal water use. A large number of wells have been drilled to supply water for irrigation. This use is seasonal and is difficult to estimate.

Estimation of the pumpage from the Claiborne, Clayton, and Providence aquifers was one of the most important aspects of this study. Municipal and industrial users of more than 100,000 gallons per day of ground water have been

required to have a permit and to report pumpage since 1972 as part of the Ground-Water Use Act. The withdrawal rates submitted in response to this requirement are based on variable measurement or estimation techniques. The most reliable reports are based on flow at the well head. Other methods used to complete the ground-water use reports include; time of pumping multiplied by the reported capacity of the pump, volume of chemicals used in water treatment, permit limit, and the number of customers multiplied by an average per-capita use. A number of permit holders, however, failed to report for at least one six month reporting period; thus there are gaps in the information base. Further complicating the estimation of pumpage rates is the fact that many of the ground-water users have wells that tap more than one aquifer (Long 1989b). Nevertheless, the total ground-water withdrawal for municipal and industrial use is reasonably well constrained, and is believed to be fairly representative.

Ground-water withdrawal reports were used in the preparation of the input data for the well package. Well records for each permitted user were examined to determine the location of the pumpage, the aquifer(s) used, and when significant changes in pumping may have occurred. Interviews with water-system superintendents were conducted when necessary information was either incomplete or questionable. These interviews were also helpful in estimating ground-water use prior to the implementation of the Ground-Water Use Act in 1972.

Reports of ground-water pumping by both municipal and industrial users are for the entire system rather than for a particular well. In instances where more than one well is used, information on the date of first (and last) use of each well is helpful in developing the data set necessary for the well package (this information is only necessary if the wells are in different cells or are constructed differently). When possible, data were gathered on which wells were used as primary sources and which were used as backup sources. Where several wells were found to be used interchangeably, the pumpage was split between the wells in relation to their reported capacity. Pumpage from multi-aquifer wells was divided among the aquifers used based upon the length of screen or open borehole in each aquifer.

Estimation of pumpage was most difficult for the City of Albany. Although the total ground-water use by the City of Albany is known within reasonable limits of accuracy, how much comes from each aquifer and from each well proved to be difficult to estimate. Albany uses a

number of wells that are spread throughout (and beyond) the city. In addition, almost every well used by the City of Albany is open to more than one aquifer. Ground-water use reports, interviews with water system personnel, well construction records, and a report on the hydrogeology of the Albany area by Hicks and others (1983) were all used to estimate and constrain the water-use data needed for the well package.

Ground-water pumpage from the Claiborne and Clayton aquifers for irrigation during the period from 1980 to 1986 is based on irrigation surveys conducted in 1981, 1984, and 1986 by the Cooperative Extension Service. Withdrawals for years for which a survey was not conducted were extrapolated based on the growing-season precipitation. However, there was a poor correlation between the growing-season precipitation and the ground-water pumpage estimates for the three years for which estimates were available. Methods used for estimating the pumpage for the years for which there were no data probably have produced estimates with no greater degree of reliability. The Cooperative Extension Service Irrigation Surveys provided pumpage estimates for each county, but the distribution of the irrigation throughout each county was not provided.

Locations used in preparation of the well package input were based on file data from the USGS's Regional Aquifer System Analysis (RASA). Irrigation withdrawal estimates for the period 1900 to 1979 are based on the pumpage used in the RASA flow model (Faye and Mayer, 1990). The average change in withdrawal for the Claiborne and Clayton aquifers during the period 1980 to 1986 was applied to the 1980 RASA estimate for the Providence aquifer to calculate estimates for irrigation from the Providence aquifer for 1980 to 1986. Ground-water pumpage for irrigation in the Claiborne, Clayton, and Providence aquifers, as used in the calibrated model, is shown in Figure II-13.

Ground-water from wells for all purposes is simulated in transient simulations of the model by use of the well package (McDonald and Harbaugh, 1988). Although wells pump water from a point location, the model simulates the pumpage as being distributed evenly over the cell in which the well lies. Wells tapping multiple aquifers are treated as separate wells for each layer being tapped, each having a specified flow rate representing the pumpage from each aquifer. More than one well in the same cell and layer can either be added together and input as a single well, or input separately; and the model sums the

pumping rates as a part of the model calculations. Changes in pumpage over time are simulated by changing the pumpage rates and/or locations of wells throughout the simulation. The transient simulations used 15 combinations of pumping rates and locations, known as stress periods (see Table 1 of text).

The initial estimates of pumpage were adjusted as a part of the calibration procedure. Although the withdrawal data are based on information and estimates having a varying degree of uncertainty, the pumpage estimates are reasonably well constrained for the larger municipal and industrial users. Therefore, changes to the well package were small in comparison to changes in other parameters. The total ground-water pumpage for each layer by stress period is shown in Figure II-14 and Table 1. The areal distribution of pumpage for the 15th and final stress period, representing 1986, is shown in Figure II-15 for layer A2, Figure II-16 for layer A3, and Figure II-17 for layer A4. The fact that a good calibration was obtained through the 86 year period of the model, indicates that the rate of ground-water pumpage through time used in the calibrated model is a reasonable estimate.

CALIBRATION

Introduction

Calibration of the digital model is necessary due to the fact that the same distribution of simulated points can be obtained from different input data. Measurements of hydrologic properties upon which the model input is based are known at only a limited number of locations and have a range of uncertainties. Therefore a range of values could be used for each data input at each cell. A trial and error calibration process of adjusting input data was used to evaluate which values for each parameter would provide the best representation of the flow system. Care was taken to ensure that input values were consistent with measured and estimated values given the unknown uncertainties of the data.

Calibration of the model was performed in the steady-state mode first. The preliminary calibration in the steady-state mode was preferable to simultaneous calibration in both the steady-state and transient modes because the steady-state flow system is not complicated by the effects of pumpage and storage. In addition, boundary flux and ground-water discharge to streams could be compared to independent estimates. Following initial calibration of the model in the steady-state mode, the additional data needed for transient

simulations were added and the calibration procedure was applied in the transient mode. Because the simulated heads from the steady-state model were used as the initial condition in the transient simulation, any change that would alter the steady-state solution had to be applied in the steady-state mode prior to its use in the transient mode.

The calibration criteria for the steady-state simulation included comparison of simulated ground-water discharge to rivers with estimated values, comparison of boundary fluxes to calculated fluxes, and comparison of simulated and observed heads. The general quality of the calibration was evaluated through use of the root-mean-square error (RMSE) statistical method. The RMSE is calculated by summing the squares of the difference between the observed and simulated heads, dividing by the number of observations, and taking the square root of the result. The RMSE was calculated for each active layer in the steady-state simulation (Table II-1). The difference between simulated and observed heads for individual observations was also used to evaluate the calibration in select areas. Simulated boundary fluxes and ground-water discharge to rivers were compared to estimated values.

Calibration criteria used in the transient mode included observed heads for stress periods for which the number of observations was sufficient for comparison and comparison of simulated and observed hydrographs. Independent flux estimates were not available for use in the transient calibration.

Possible Sources of Error in Observed Head Data

A major concern in the calibration process are the data to which the simulated heads were being compared. Care was taken to ensure that the construction of the well from which a measurement was taken was known and that the well was open to only one aquifer. Head measurements from the Providence aquifer are sparse because many of the Providence aquifer wells also are open to other aquifers. The paucity of data available for wells open to only the Providence aquifer necessitated the use of data from wells suspected of tapping aquifers in addition to the Providence aquifer. Differences between the observed head for the multi-aquifer wells and simulated heads were included in the calculations of RMSE, but were evaluated on a case-by-case basis depending upon the magnitude of the difference and the construction of the well.

The location of the screened or open interval

within the aquifer is an important factor in the observed head, especially in the area of unconfined flow where vertical head gradients within each aquifer would be expected to be significant. A well located on a hill top that is screened in the upper part of an unconfined aquifer might have a higher head than a well at the same location, but screened in the base of the aquifer. Differences in head of several tens of feet between the local and intermediate or regional flow systems could be expected. The effect of vertical gradients is greatest in areas having significant relief in unconfined areas and diminishes as the aquifer becomes more confined and relief decreases. Wells having shallow screen or open intervals are most likely to reflect the local flow system. Wells that were considered to represent the local flow system were excluded from the data sets of observed heads to which the simulated heads were compared.

Most of the head measurements that are reported in the literature and in data files are based on depth to water in production wells. These measurements are assumed to have been taken under static conditions. However, the time since the well was pumped often is not known. A water-level measurement made shortly after the well was pumped may be influenced by the pumpage of the well, resulting in head that is lower than the actual static head. The amount of time needed for the well to 'recover' from a period of pumping to the static water level varies greatly from well to well. Factors that influence the recovery rate include the pumping rate, the well construction, and the aquifer characteristics. How many observed head measurements that are effected by prior pumpage is not known. Because it is not known which observed head values may be effected, correction to the observed data is not possible.

The observed head is calculated by subtracting the depth to water in the well from the elevation of the measuring point. The elevation of the measuring point was estimated from a 7.5 minute topographic map. The elevation of a properly located point on a topographic map is generally considered to have a possible error of plus or minus half the contour interval of the map.

Short-term fluctuations in the water level in these aquifers can range 20 feet or more under non-pumping conditions (McFadden and Perriello, 1983). The fluctuation can be greater in areas of significant seasonal pumpage, such as irrigation. The shortest period in the digital model is one year; therefore, seasonal fluctuations are not addressed in the model. Comparisons between

observed and simulated heads were made using water-level data collected at a variety of times throughout the year. Most observations used in the calibration of the model in the transient mode were made in the fall, when water levels are historically at their lowest level.

Observed head data used in the steady-state calibration and in the calibration of period 2 (1945-1959) were collected in a variety of seasons, and over a range of years. The climatic and pumping conditions associated with these measurements are unknown. In other stress periods, observed head measurements were made in a single year; and all observed head measurements are affected by the same conditions. Because pumpage was relatively small during this time period, fluctuations due to pumpage would be expected to be small. Although it is not known to what extent these factors affect the observed head measurements, they are considered to represent the long-term average head in the aquifer system for the time period represented by period 2.

The simulated heads to which the observed heads are compared represent the average head over the area of the cell, whereas the observed head represents the head only at the point of the measurement. Observed head in the intermediate or regional flow system may vary as much as 20 feet within the area of a single cell. Ideally the simulated head for a cell would be compared to observed head measured in a well located at the center of the cell, which would be assumed to be the average head within the cell. In most instances, the observed data were from wells that are not at the center of the cell. The effect of the location of the well is greatest for wells located in areas of steep potentiometric gradient, such as in areas of large ground-water pumpage. The model grid was designed, therefore, to have smaller cells in the areas of steep gradients to minimize this effect. A decision was made to not attempt to adjust the observed head to reflect the head at the center of the cell. This decision was based on the fact that few wells are located at the extreme edges of cells and other possible sources of error in the observed-head data.

The criteria for evaluating the calibration of the model must consider the sources of possible error noted above. Although every effort was made to reduce the possible error in the observed head used for comparison with the simulated heads, several potential sources of error could not be eliminated. Given these possible sources of error, RMSE of 25 feet or less were arbitrarily considered to be reasonable for the overall calibration of the model. An absolute difference

between observed and simulated head for each observation of 40 feet or more was considered to be cause for a more detailed evaluation of both the quality of the calibration in that area as well as the reliability of the observed data.

Model Results

The output of the calibrated model includes simulated head for each active layer and simulated fluxes to and from all sources and sinks. In comparing potentiometric surfaces simulated by the digital model to published data, it must be recognized that the heads simulated by the model represents flow in the intermediate and regional flow systems only. Published potentiometric surfaces commonly are based on head measurements reflecting the local flow system in addition to the intermediate and regional flow systems.

Steady-State Simulation

Simulated heads from the steady-state simulation compare well with observed heads. The RMSE for each model layer is less than the 25 and 40 foot target values noted earlier. Given the uncertainties in the observed data, the differences in the simulated and observed heads are considered reasonable. Simulated heads for layer A2 were compared to 72 observed heads from the Claiborne aquifer, whereas the number of observations from the Clayton and Providence aquifers were 19 and 11 respectively.

The steady-state simulated potentiometric surface for layer A2 is shown in Figure II-18. The general flow paths indicated by the potentiometric surface are similar to those that would be expected from the conceptual model. A comparison of the simulated potentiometric surface (Figure II-18) with the published predevelopment potentiometric surface of the Claiborne aquifer (Figure 5) from McFadden and Perriello (1983) indicates that in the updip area, the potentiometric surface based on the observed data is much more irregular. The reason for this difference is the inclusion of observed heads from shallow wells representing the local flow system and the use of stream elevations in the outcrop area in the construction of the contours. Both the shallow wells and the stream elevations in the outcrop areas reflect the local ground-water flow system. The simulated potentiometric surface in the confined area of layer A2 is quite similar to the down-dip part of the predevelopment potentiometric surface of the Claiborne aquifer.

Simulated heads for layer A3 are shown in Figure II-19. The distribution of heads and the

direction of flow is consistent with the conceptual model and with published information. The simulated potentiometric surface is similar to the published pre-development surface of McFadden and Perriello (1983) for the Clayton aquifer (Figure 6). Table II-1 indicates that the match between simulated and observed heads is not as good for the Clayton aquifer as it is for the Claiborne aquifer. Simulated heads in the area of Dawson, in Terrell County, generally are higher than observed heads. The number of observations for this area suggests that the observed heads in the Clayton aquifer in this area reflect some degree of development of the aquifer rather than a predevelopment condition. Simulated heads, reflecting a predevelopment condition would be expected to be higher than the observed heads, which reflect a stressed condition.

The simulated potentiometric surface for layer A4 is shown in Figure II-20. Figure II-20 is similar to what the potentiometric map of Clarke and others (1983) would be if stream control were not used in the plotting of the contours. The RMSE associated with layer A4 was similar to that associated with layer A3 (Table II-1). However, the mean absolute difference between simulated and observed heads was greater for layer A4. Some of the observed heads to which the simulated heads were compared are for wells open to more than one aquifer. As noted earlier, there are few wells that tap only the Providence aquifer.

The estimated discharge to streams and rivers during the 1954 drought, along with the minimum and maximum values (based on the uncertainties in the measurement process) are shown in Table II-2. Simulated flux to rivers and streams generally falls within the range given for each stream segment. Simulated discharge to the middle reach of Muckalee Creek and the lower reach of Kinchafoonee Creek are greater than the maximum estimated. The simulated discharge to Nochaway Creek is less than the minimum estimated discharge.

Flux into and out of the specified-head cells was compared with ground-water flow estimated from unpublished potentiometric surfaces representative of the intermediate and regional flow systems. The estimated flux to which the simulated flux was compared is based upon sparse data, and has a relatively large margin of error. Figures II-21a and II-21b present the simulated fluxes across portions of the lateral boundaries of layers A2 and A3, respectively. Estimated flux is indicated for the section of the boundary for which reasonable estimates could be computed. The simulated flux generally is within 0.5 cfs of the estimate for each segment, a reasonable match, given the uncertainties of the estimated flux. The only segment that had a simulated flux significantly different (i.e., 1.28 cfs) from the estimated flux was the segment on the southwest boundary of layer A3 (Figure II-21b). Estimation of the flux for this segment was particularly difficult due to convoluted contours in the vicinity of the Chattahoochee River.

Estimated and boundary fluxes simulated for layer A4 are indicated in Figure II-21c. The difference between simulated and estimated fluxes is larger for all segments of layer A4 than for layers A2 and A3. Data upon which the estimates were based are much more sparse for this layer than for the other layers.

Boundary fluxes, recharge, discharge to rivers, and inter-aquifer leakage simulated by the model in the steady-state mode are shown in Figure II-22. Simulated flux into and out of layer A2 across confining unit C1 (overlying A2) results in a net upward flux of 8.9 cfs. The digital model was developed to include outliers and some updip parts of the Upper Floridan aquifer (otherwise simulated by layer A1) within layer A2. This results in some of the leakage from the Upper Floridan aquifer to the Claiborne aquifer being represented as recharge to layer A2 rather than as leakage. Downward leakage from A1 to A2 primarily is in the updip parts of the confined areas. Upward leakage from A2 to A1 is broadly distributed in the southern part of the model and near streams.

Vertical flux across confining unit C2 is closely balanced between upward and downward movement. Net flux is 0.4 cfs upward. Downward flux from A2 to A3 is located almost exclusively in the northern portion of the area in which the confining unit exists. The greatest downward flux is in the vicinity of the interstream divides of layer A2. Upward flux from A3 to A2 is greatest in the vicinity of the regional streams. Upward flux is particularly high along the Flint River where incision of the river into the confining unit is represented in the model by higher leakance. Vertical flux in the southern part of the model area is uniformly upward, but at very low rates.

The net flux across confining unit C3 is 28.7 cfs downward. Downward leakage from A3 to A4 is broadly distributed across the northern part of the area in which confining unit C3 exists. The rate of downward leakage is greatest in the interstream areas of layer A3. An exception to the trend of downward leakage is in the area of streams, where much of the upward flow from A4 to A3 is concentrated, particularly along the Chattahoochee River. Low vertical flux is

simulated in the southern part of the model. The direction of flow varies, but upward flow is more common.

Vertical flow simulated by the model is consistent with the conceptual model. Water recharges the aquifer in the interstream area and flows either laterally to streams, or downward across one or more confining units and then laterally to streams, possibly moving upward through a confining unit to reach the stream. The relatively low rates of flow down the dip of the aquifer are a result of the lack of a ready outlet for the water. Upward movement was the primary discharge path for ground-water system prior to development. The low hydraulic conductivity of the confining units results in the flow rates associated with this path being small.

Transient Simulation

Calibration of the digital model under transient involved comparison of simulated heads with historical observed heads. Observed heads sufficient for comparison were available for all aquifers at times corresponding to period 2 (1945-1959), period 8 (1978-1979), period 13 (1984), and period 15 (1986). Observed heads for the Providence aquifer were available for period 9 (1980), and for the Claiborne and Clayton aquifers for periods 10 and 11 (1981 and 1982, respectively). The RMSE and number of observed heads by layer for each of the stress periods used in the calibration is shown in Table III-3. The RMSE generally lies within 25 feet, which was noted previously as being indicative of a reasonable calibration. The higher RMSE values result from relatively large differences between simulated and observed heads for a small number of wells; but the majority of the simulated heads are nearly the same as the observed heads.

The simulated potentiometric surface for layer A2 at the end of period 15 is shown in Figure II-23. The simulated surface compares well with the potentiometric surface of the Claiborne aquifer for the fall of 1986 (Long, 1989a) (Figure II-24). The major difference between the two surfaces probably is due to the exclusion of local flow in the simulated surface.

Figure II-25 shows the simulated potentiometric surface for layer A3. A comparison of this surface with the fall 1986 potentiometric surface for the Clayton aquifer, shown in Figure II-26 (Long, 1989a), indicates a close resemblance between the two surfaces. Simulated heads in Calhoun and southern Terrell Counties are somewhat higher than indicated in the observed surface.

The simulated potentiometric surface for layer A4 is shown in Figure II-27. The simulated surface is different in the Americus area than the 1986 potentiometric surface for the Providence aquifer shown in Figure II-28 (Clarke, et al, 1987). The differences between simulated and observed heads in this area, however, are small. In most other areas, the simulated and observed potentiometric surfaces are similar, considering the observed heads from wells representing the local flow system and elevations of streams in the outcrop area were used in preparing the potentiometric surface map.

Simulated Hydrographs

Comparison of a hydrograph of the simulated head of a cell to an observed hydrograph for a well in that cell provides an additional method of evaluating the calibration of the model under transient conditions. A close fit between the simulated hydrograph and the observed data provides validation that the model is capable of reproducing known hydrologic conditions.

Data adequate for the construction of hydrographs for wells in the Claiborne aquifer are limited to a fairly small area. Observed heads for the USGS's test well 4 in western Dougherty County, and simulated heads for the cell in which it is located are shown in Figure II-29a. The trend of the simulated heads follows the observed heads fairly well. The low heads observed in late 1980 and early 1981 are not reflected in the simulated heads. The simulated heads, however, reflect the average head over the entire area of the cell rather than at a particular point. Observed heads for the USGS's test well 2 in Dougherty County and simulated heads for the cell representing that area are shown in Figure II-29b. The overall trend in the simulated heads follows the observed heads reasonably well. Figure II-30a shows the observed heads for the W. H. Fryer well in Lee County and simulated heads for the corresponding cell. The high observed heads measured in 1983 and 1984 are not reflected in the simulated heads. Deviations of the simulated head from the observed heads in 1983 and 1984 in Figures II-29b and II-30a may be related to inaccurate estimates of ground-water pumpage for irrigation. The difference between simulated and observed heads was well within the acceptable range discussed previously.

Data enabling the construction of hydrographs displaying the comparison between simulated and observed heads were available for a number of widely distributed wells in the Clayton aquifer. The hydrograph for a former City of Cuthbert well

that has been equipped with a water-level recorder is shown in Figure II-30b. This well is relatively shallow, completed in the upper part of the aquifer. Thus, the well probably has a component of local flow, resulting in heads that are consistently higher than simulated the Don Foster well in Terrell County, and the H.T. McClendon well in Calhoun County are shown in Figure II-31 a and b, respectively. Although these hydrographs are based on only a few head measurements, it can be seen that the trends of the heads. The trend of the simulated heads follows the trend of the observed heads closely. Hydrographs of simulated heads match the observed trend from the well. Figures II-32a and b and II-33a show the hydrographs of three wells equipped with water-level recorders. Each of these hydrographs show excellent agreement between observed and simulated heads. Observed head from wells in the Providence aquifer were not adequate to construct meaningful hydrographs.

Fluxes

The output of interest in most modeling studies is the distribution of simulated heads resulting from the initial and boundary conditions specified in a simulation. In a ground-water flow system such as the Claiborne, Clayton, and Providence aquifer system, changes in flux within the system are equally as important as simulated head. Fluxes of interest include leakage between aquifers, horizontal flow to and from specified head cells, ground-water discharge to rivers, and release of water from storage. Changes in these fluxes over the period of the simulation are due to changes in pumpage, as recharge and other input data are held constant throughout the simulation.

The simulated release of water from storage through the 15 stress periods of the transient model is shown in Figure II-33b. Simulated flux from storage is given for the entire model rather than by layer basis. The total pumping rate by stress period is also shown. The relation between the pumping rate and the release from storage is clearly evident.

The simulated ground-water discharge to rivers for layers A2, A3, and A4 for selected stress periods is shown in Figure II-34a. Little change was simulated in this flux over the period of simulation. The difference between the simulated ground-water discharge to rivers in the steady state (identified in Figure II-22) and at the end of the transient simulation (SP15) was only 21 cfs, a 4 percent difference. The largest difference, a 7 percent decrease, was for layer A3. The small changes in river flux are probably due to the

distance of the river cells from the bulk of the ground-water withdrawal. Simulated head in the updip area of each layer did not change much over the period of simulation. Simulated ground-water discharge to rivers would vary more if annual changes in the recharge rate were simulated.

Simulated vertical flux across the confining units changed dramatically over the period of the transient simulation. Figure II-34b shows the net vertical flux across each confining unit. Vertical flow across confining unit C1 had a net upward component of 8.9 cfs in the steady-state simulation (see Figure II-22). With stress, the vertical flux became more balanced between upward and downward components through stress period 9. The net flux across C1 became downward in stress period 10. At the end of the simulation, the net flux across C1 was simulated to be 6.2 cfs downward from A1 into A2. It seems that water that under predevelopment conditions would flow upward into A1 is being diverted to pumping.

The simulated net vertical flux across confining unit C2 was essentially balanced in the steady-state simulation. As pumpage increased, the simulated flux developed a strongly downward component. At the end of the transient simulation, the net downward flux was 8.6 cfs. The simulated vertical flux across C2 had the smallest absolute change of the three confining units. However the magnitude of the change in relation to the relatively smaller pumping rate in layer A3 compared to A2 demonstrates the degree to which layer A3 is stressed.

Ground-water movement across confining unit C3 is predominantly downward. Much of the downward movement is concentrated in the updip part of the layer, where much of the water moves toward river cells. The decrease in net downward flux probably is more a response to increasing upward flux than to decreasing downward flux. The increasing upward flux reflects changes in pumpage in layer A3. This reinforces the finding that layer A3 is under great stress in the later stress periods of the simulation.

Horizontal fluxes from specified head cells for each layer are shown in Figure II-35. Horizontal fluxes from specified head cells in layer A3 changed little over the period of the transient simulation. Fluxes within layer A4 also changed little. Horizontal fluxes from specified head cells in layer A2 increased approximately 10 cfs for fluxes into the layer, and decreased approximately 6 cfs for fluxes leaving the layer. Changes in boundary fluxes of this magnitude usually indicate a boundary that is located too close to an area of stress. This seems to be the case with this model.

Pumpage for the City of Cordele is located just a few miles from the southeastern boundary of layer A2, as are several other smaller pumpages.

Summary

The calibration of a digital model commonly is based on head matching. As noted above, the heads simulated by the digital model in both the steady-state and transient simulations generally match the observed heads to within the limits of accuracy of the data. For the steady-state simulation, fluxes to rivers are within the range of values observed or estimated from the 1954, drought and simulated boundary fluxes are reasonably close to estimated values. A match between the hydrographs of simulated heads with observed data was achieved in the transient simulation. This match between simulated and observed heads as well as the simulated fluxes being reasonably close to estimated fluxes adds to the level of confidence in the calibration of the model. These same findings provide further validation that the model is capable of simulating known hydrologic events and conditions. This suggests that the model can be used to predict the general response of the aquifer to future changes in the distribution of pumpage and recharge.

SENSITIVITY ANALYSIS

A sensitivity analysis was performed to qualitatively assess the response of the model to uniform changes in model parameters. The sensitivity analysis also was useful in validating the conceptual model upon which the digital model was based. The objective of the sensitivity analysis was to evaluate which hydrologic factors, when changed from calibrated values, would produce the greatest change in simulated heads and model fluxes.

The sensitivity analysis was conducted by uniformly changing one hydrologic parameter while the other parameters were held at calibrated values. Hydrologic parameters investigated in the sensitivity analysis included (1) river stage, (2) recharge, (3) river bed flux, (4) pumpage, (5) transmissivity, (6) leakance, and (7) storativity. Simulations were made using a number of different multipliers for each factor. The sensitivity of the model to changing parameters was evaluated by comparing the simulated heads and fluxes to the calibrated heads and fluxes.

The results of the sensitivity analysis indicate that the model is most sensitive to variation of the recharge rate, pumping rate, and transmissivity. The model, as a whole, is only moderately sensitive

to the vertical hydraulic conductivity of the confining units and the aquifer storativity. The model is insensitive to the riverbed conductance.

Well pumpage has a greater effect on simulated heads than any of other parameter included in the sensitivity analysis. The effect of changes in well pumpage is more pronounced in layers A3 (Clayton Aquifer) and A4 (Providence Aquifer) than in A2 (Claiborne Aquifer).

Simulated heads were found to be almost as sensitive to changes in recharge as they were to well pumpage. The primary reason that the model is sensitive to changes in recharge is that recharge is the largest flux in the model. The sensitivity of simulated heads to changes in recharge would be greater except that river fluxes are closely related to the recharge, accepting a large part of the change. The sensitivity analysis indicates that simulated heads are sensitive to changes in transmissivity values.

The response of simulated heads to changes in the leakance of the confining units and storativity indicates that the model is only moderately sensitive to these parameters. Conductance of riverbeds was the least sensitivity of all the parameters included in the sensitivity analysis.

Model layer	Number of observations	RMSE
A2	72	16.8
A3	19	20.6
A4	11	20.0

Table II-1. Root mean square error and number of observations for calibrated model in steady-state mode.

River	Layer(s)	Simulated Discharge	Est. Discharge Mean	Est. Discharge Minimum	Est. Discharge Maximum
Flint River	A2, A3, A4	74.4	53	7	99
Muckalee Creek	A4	8.9	9	8	10
Muckalee Creek	A2, A3	19.7	12	9	15
Muckalee Creek	A2	25.9	35	26	44
Kinchafoonee Creek	A4	18.7	21	15	28
Kinchafoonee Creek	A2, A3, A4	39.2	24	11	38
Little Nochaway Creek	A2	20.9	24	21	27
Ichawaynochaway Creek	A2	33.4	36	11	61
Nochaway Creek	A2	16.3	24	21	27
Pachitla/Carter Creek	A2	48.8	49	42	56
Pataula Creek	A4	10.8	12	10	14
Pataula/Hodchodkee Creek	A4	67.5	70	59	81
Pataula Creek	A4	13.7	17	13	21
Chattahoochee River	A3, A4	59.0	26	0	109

Table II-2. Simulated and estimated ground-water discharge to rivers, in cubic feet per second.

Stress Period	Layer A2		Layer A3		Layer A4	
	n	RMSE	n	RMSE	n	RMSE
2	35	18.3	34	20.1	10	24.3
8	47	21.6	48	24.2	9	21.2
9					12	25.9
10	55	20.5	59	20.6		
11	55	19.6	61	18.7		
13	50	19.7	57	23.3	13	23.4
15	53	21.6	53	25.8	13	23.4

Table II-3. Root mean square error and number of observations for stress periods used in transient calibration.
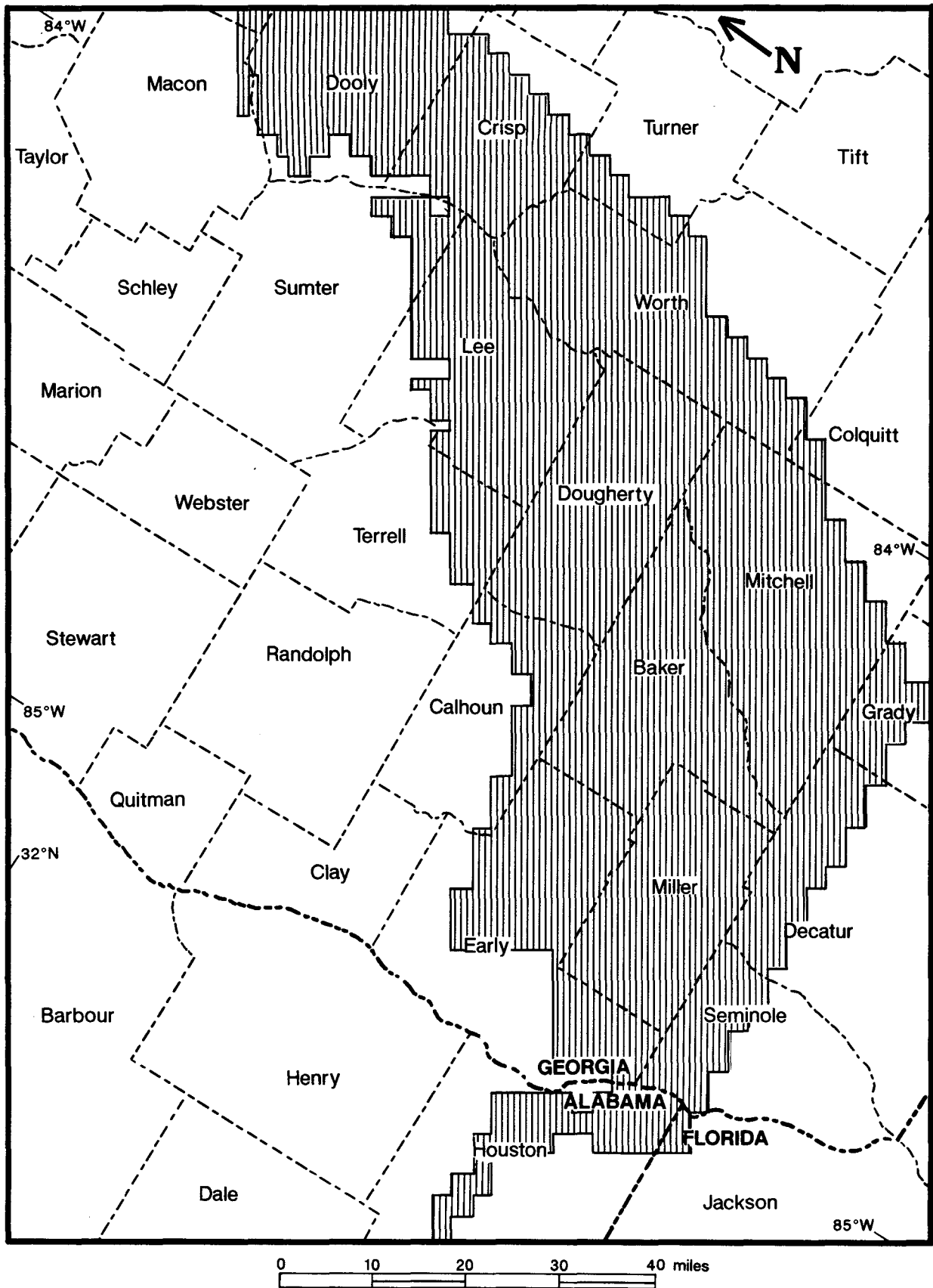
Figure II-1. Boundary for model layer A1. All heads are specified. Patterned area represents the outcrop area of the Upper Floridan aquifer.
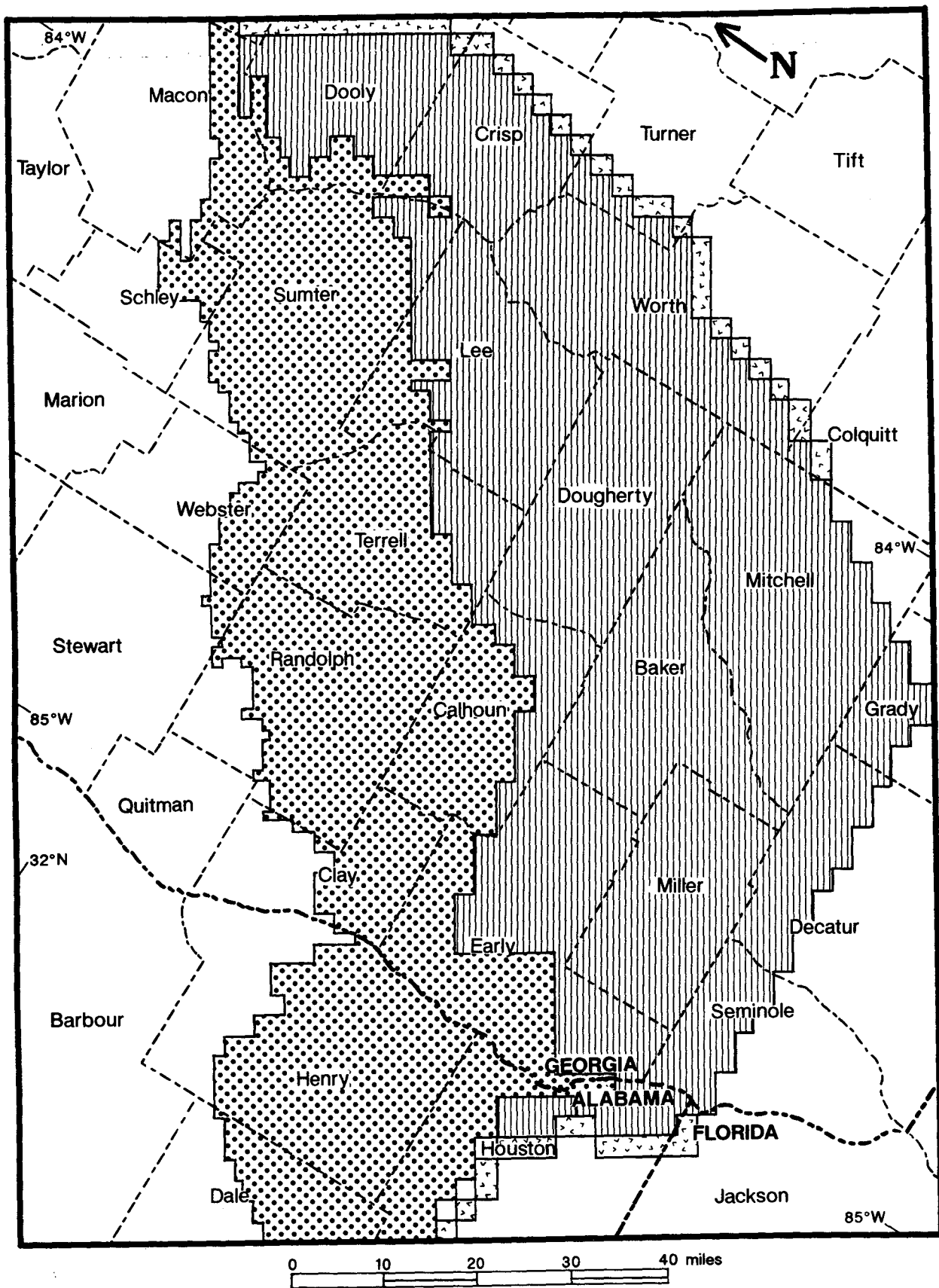
Figure II-2. Outcrop, active, and specified head cells in model layer A2. Dot pattern represents the outcrop area of the Claiborne aquifer; the line pattern represents the additional active area; and the random "v" pattern represents the specified head cells.
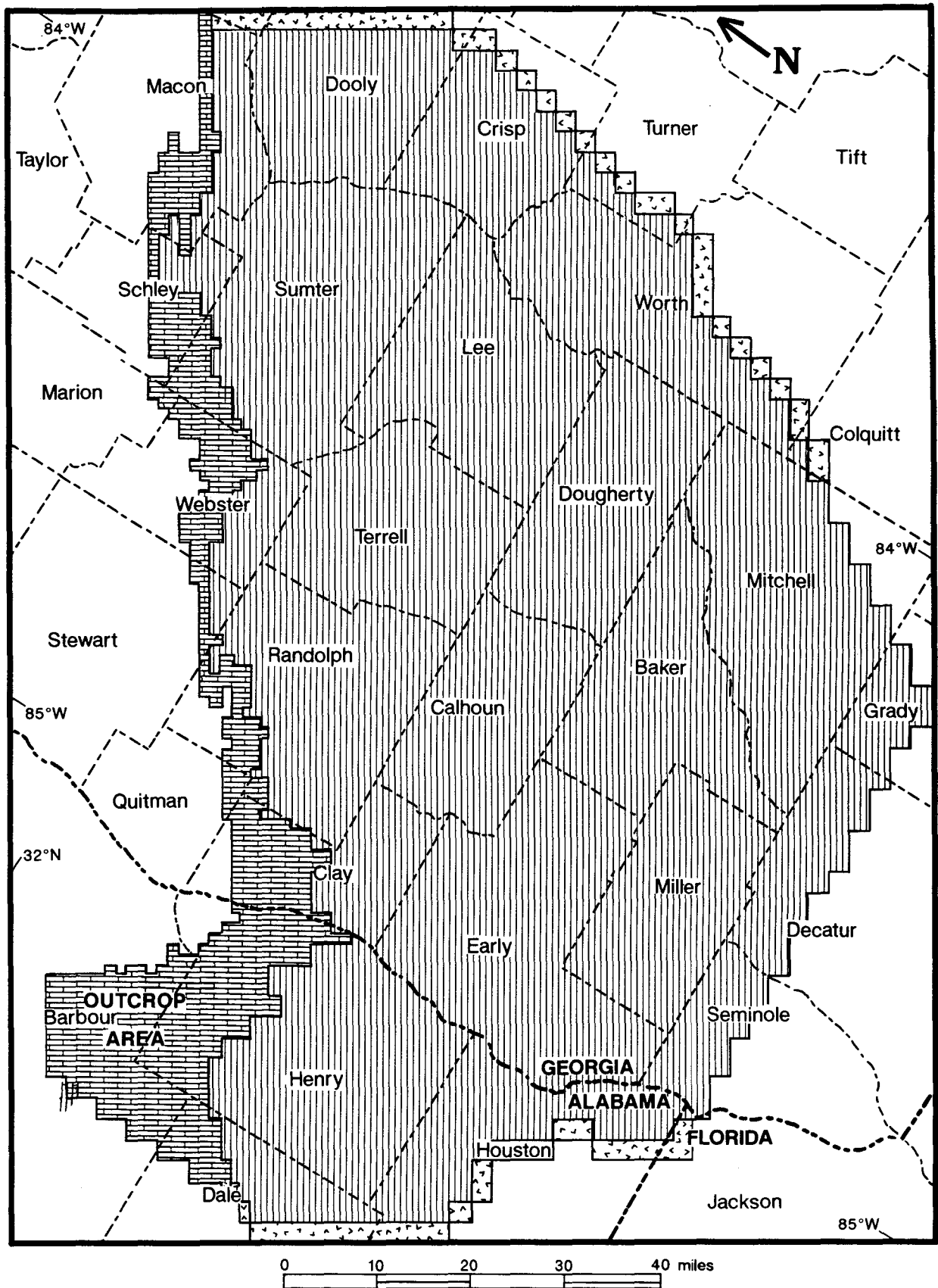
Figure II-3. Outcrop, active, and specified head cells in model layer A3. Brick pattern represents the outcrop area of the Clayton aquifer; the line pattern represents the additional active area; and the random "v" pattern represents the specified head cells.
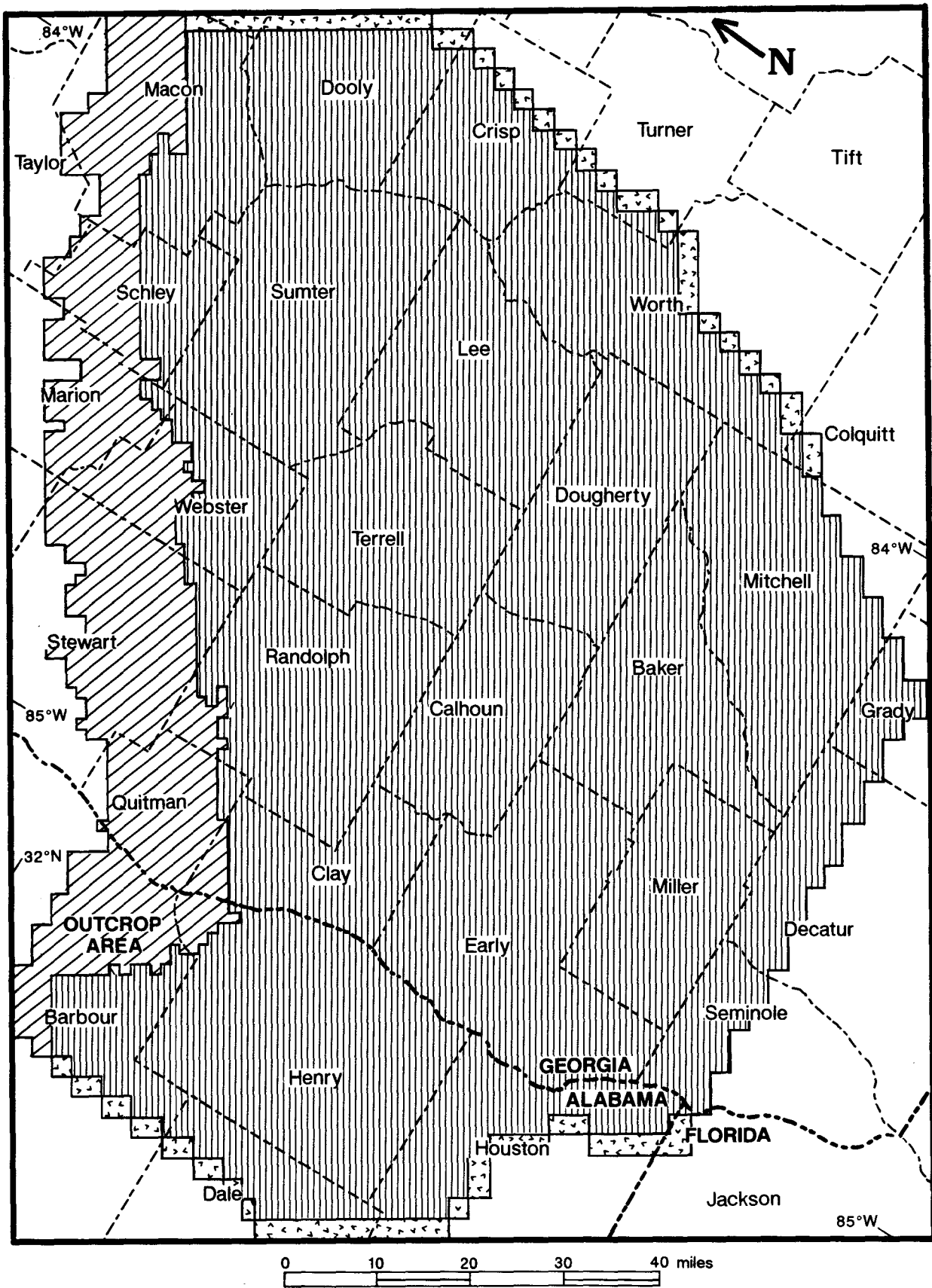
Figure II-4. Outcrop, active, and specified head cells in model layer A4. Diagonal pattern represents the outcrop area of the Providence aquifer; the line pattern represents the additional active area; and the random "v" pattern represents the specified head cells.
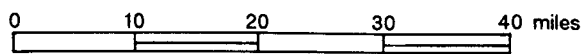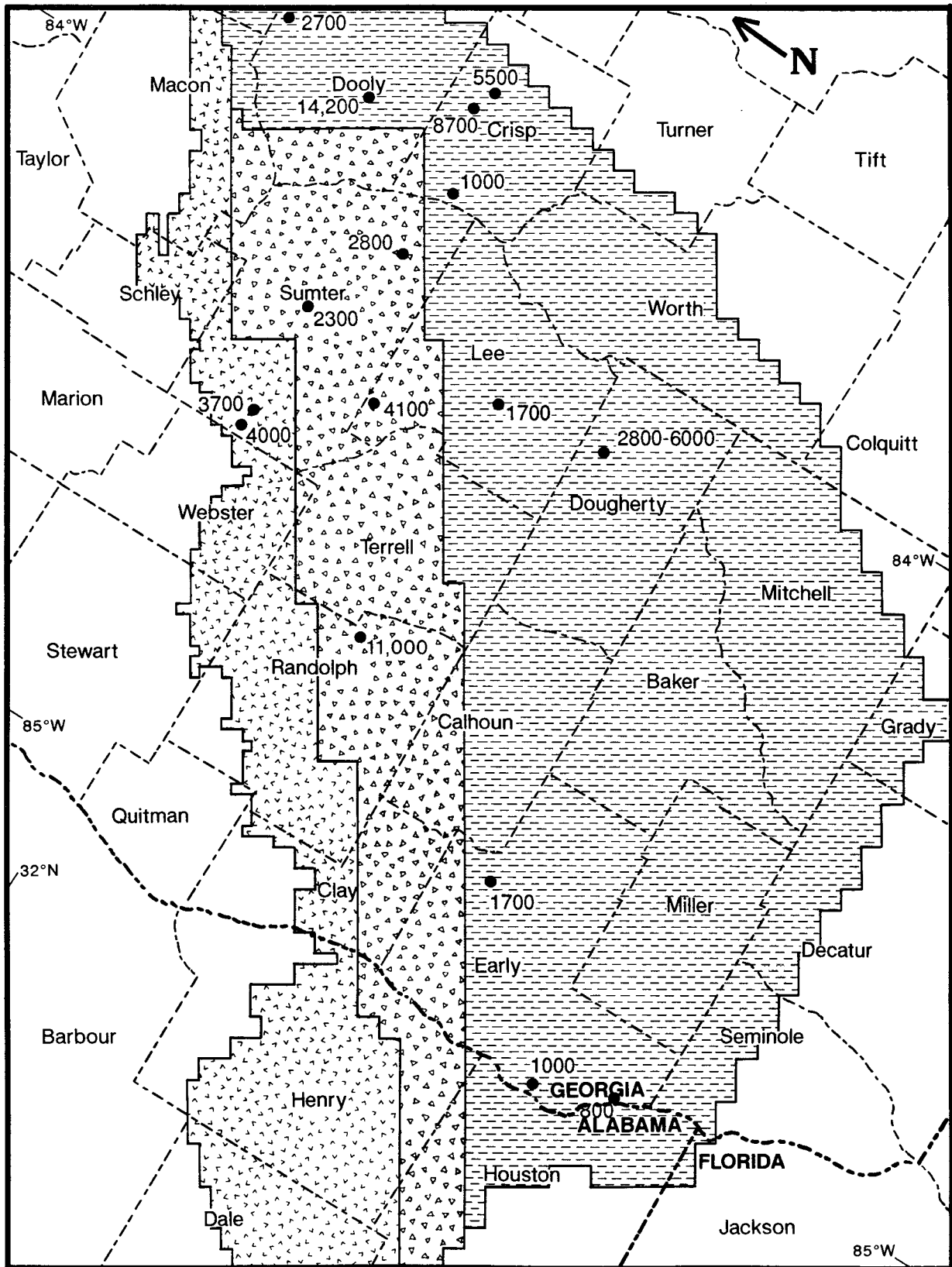
Figure II-5. Transmissivity for model layer A2. Black dots are estimated transmissivities from McFadden and Perriello, 1983.
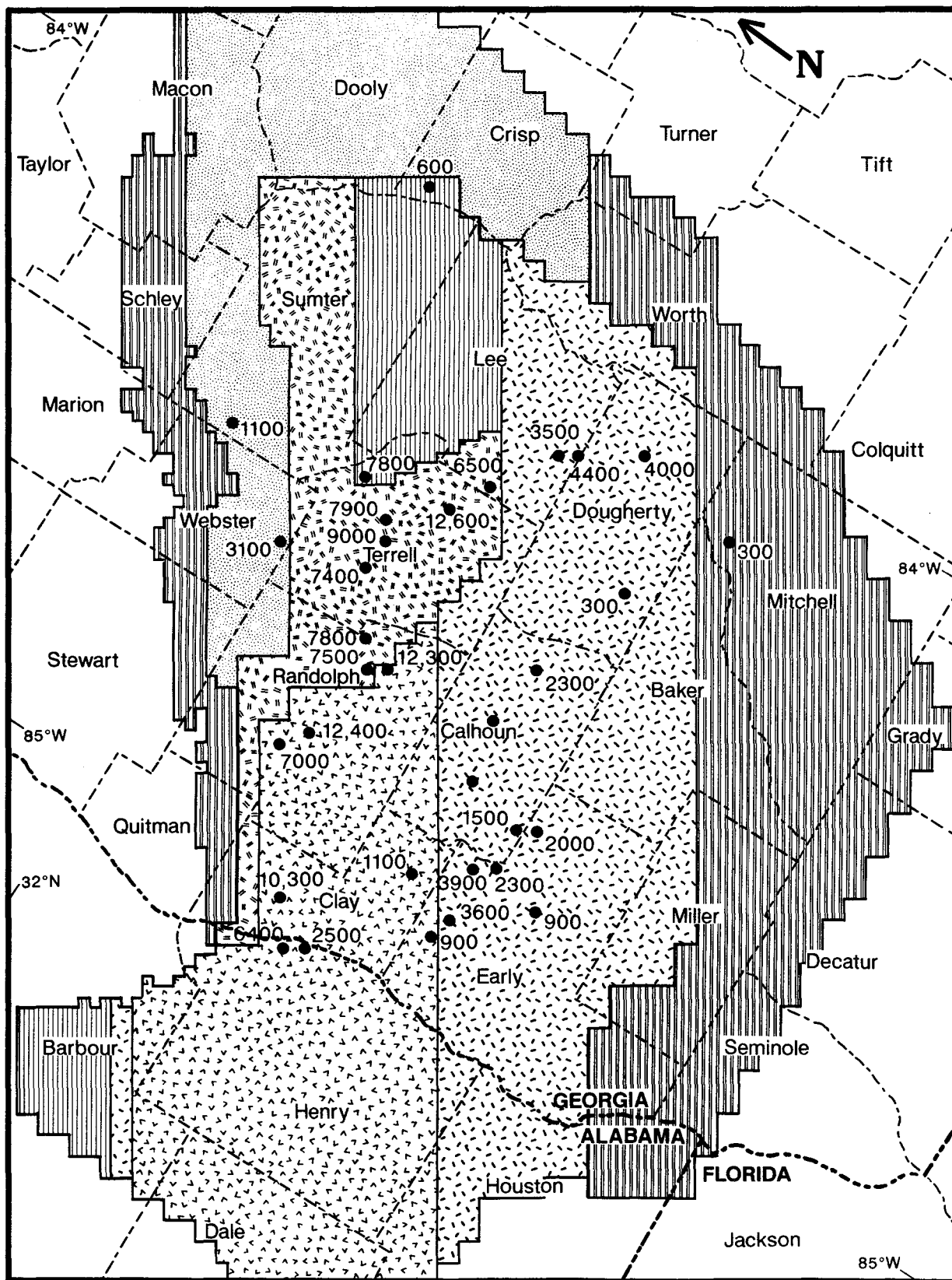
Figure II-6. Transmissivity for model layer A3. Black dots are estimated transmissivities from McFadden and Perriello, 1983.
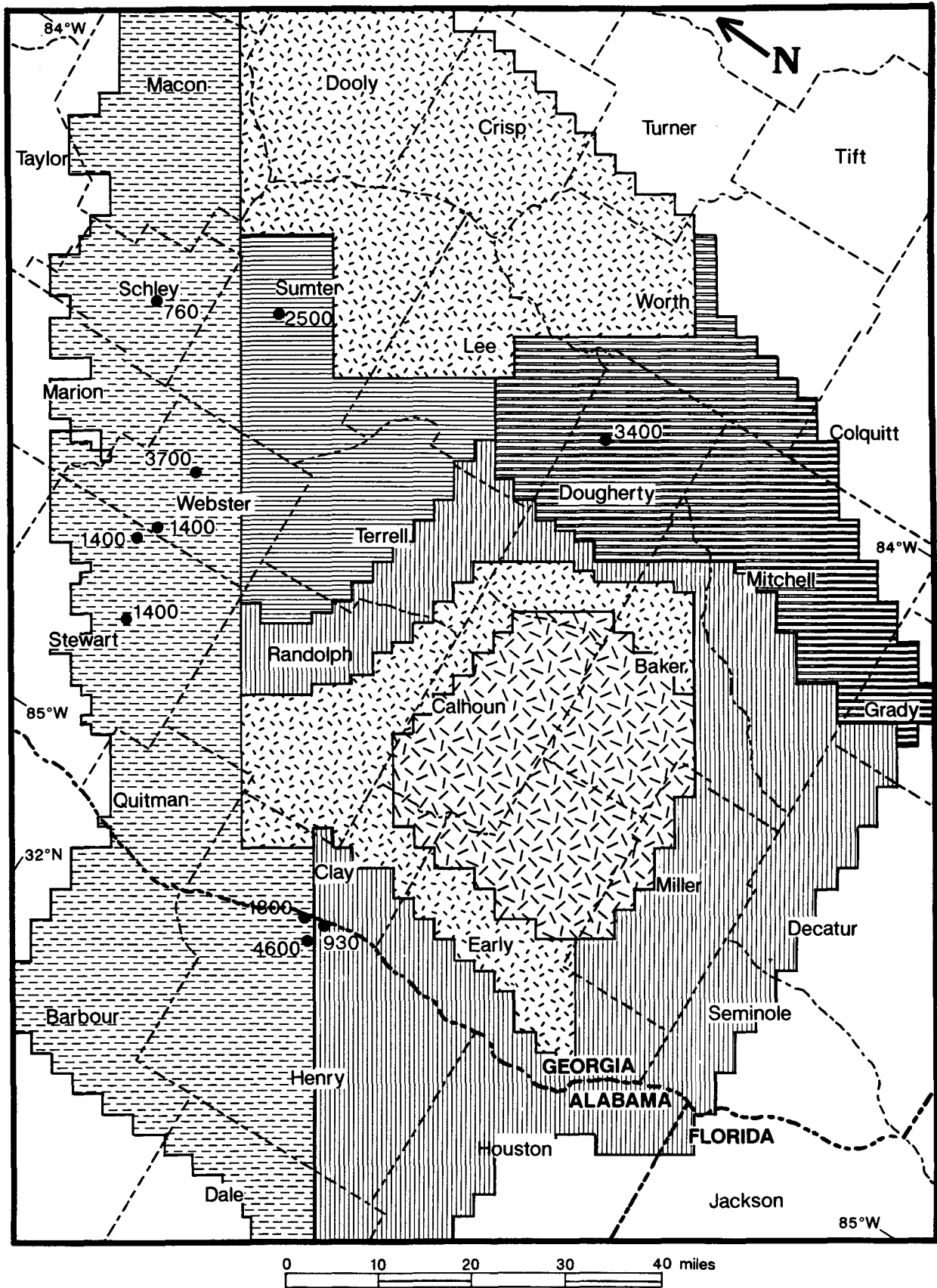
Figure II-7. Transmissivity for model layer A4. Black dots are estimated transmissivities from Clarke and others, 1983.
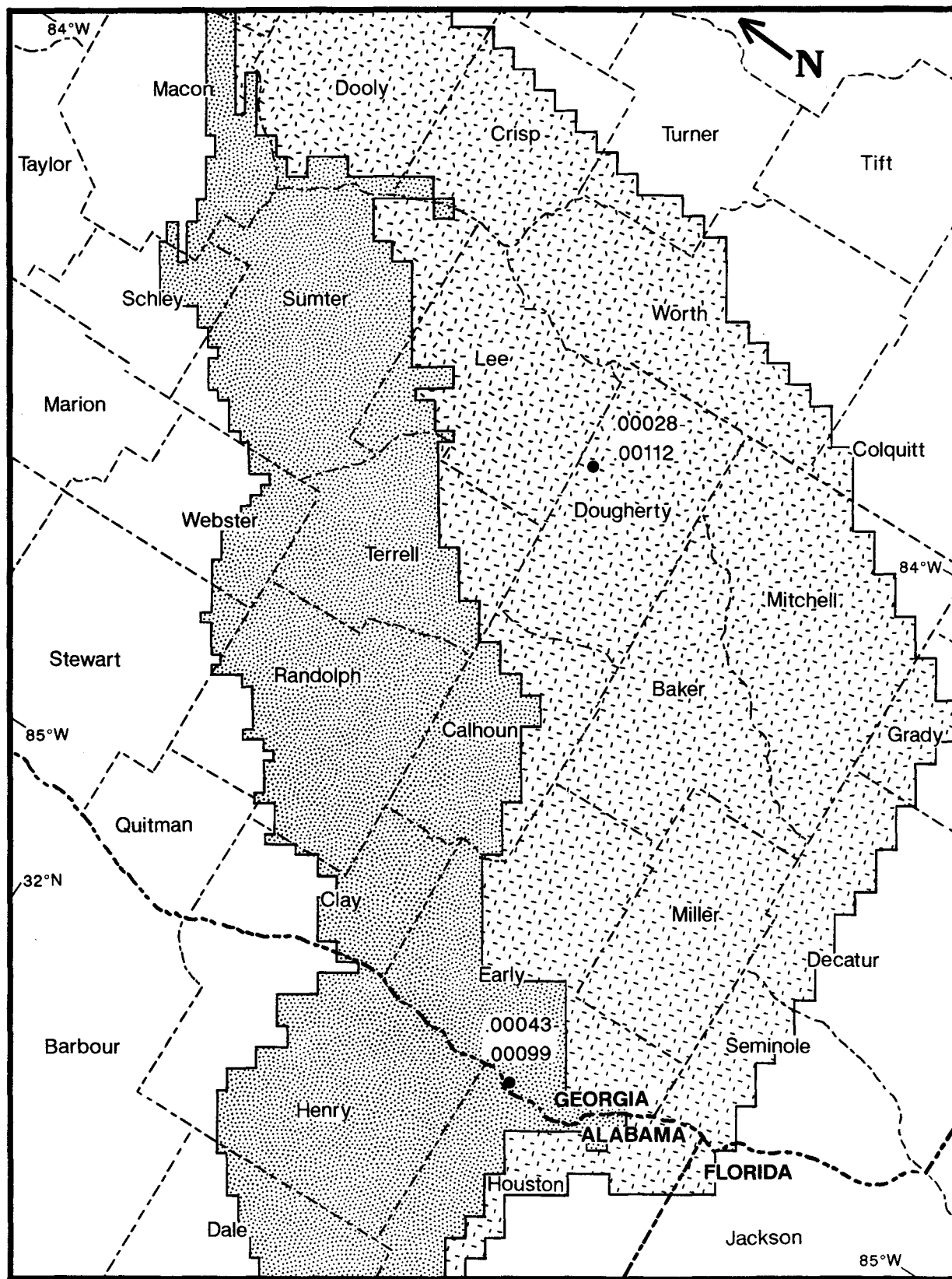
Figure II-8. Calibrated storage for model layer A2. Black dots are reported values from McFadden and Perriello, 1983.
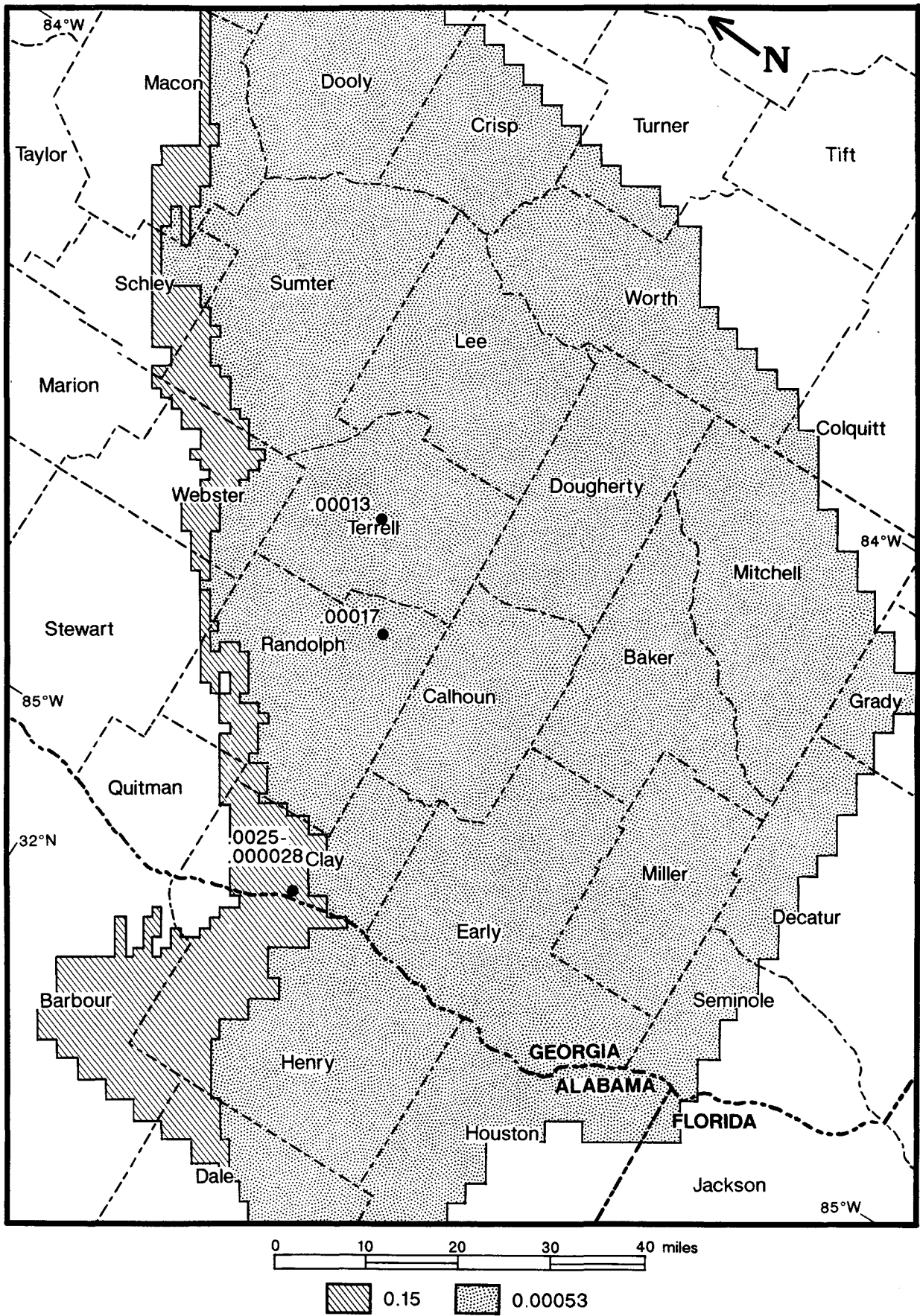
Figure II-9. Calibrated storage for model layer A3. Black dots are reported values from McFadden and Perriello, 1983.
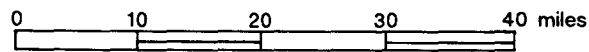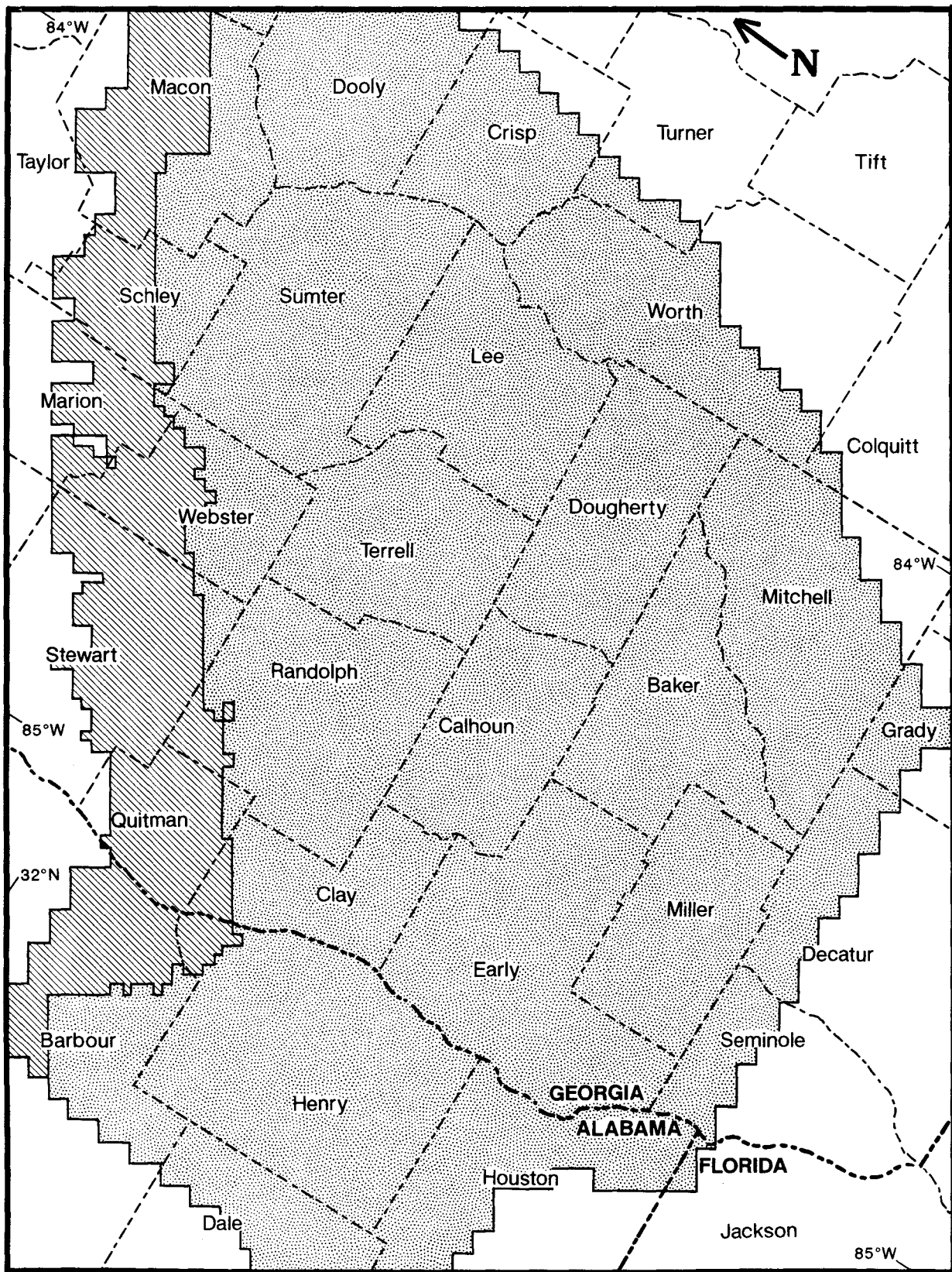
Figure II-10. Calibrated storage for model layer A4.
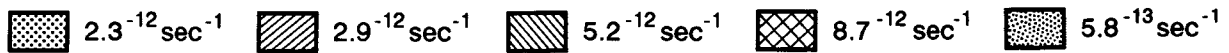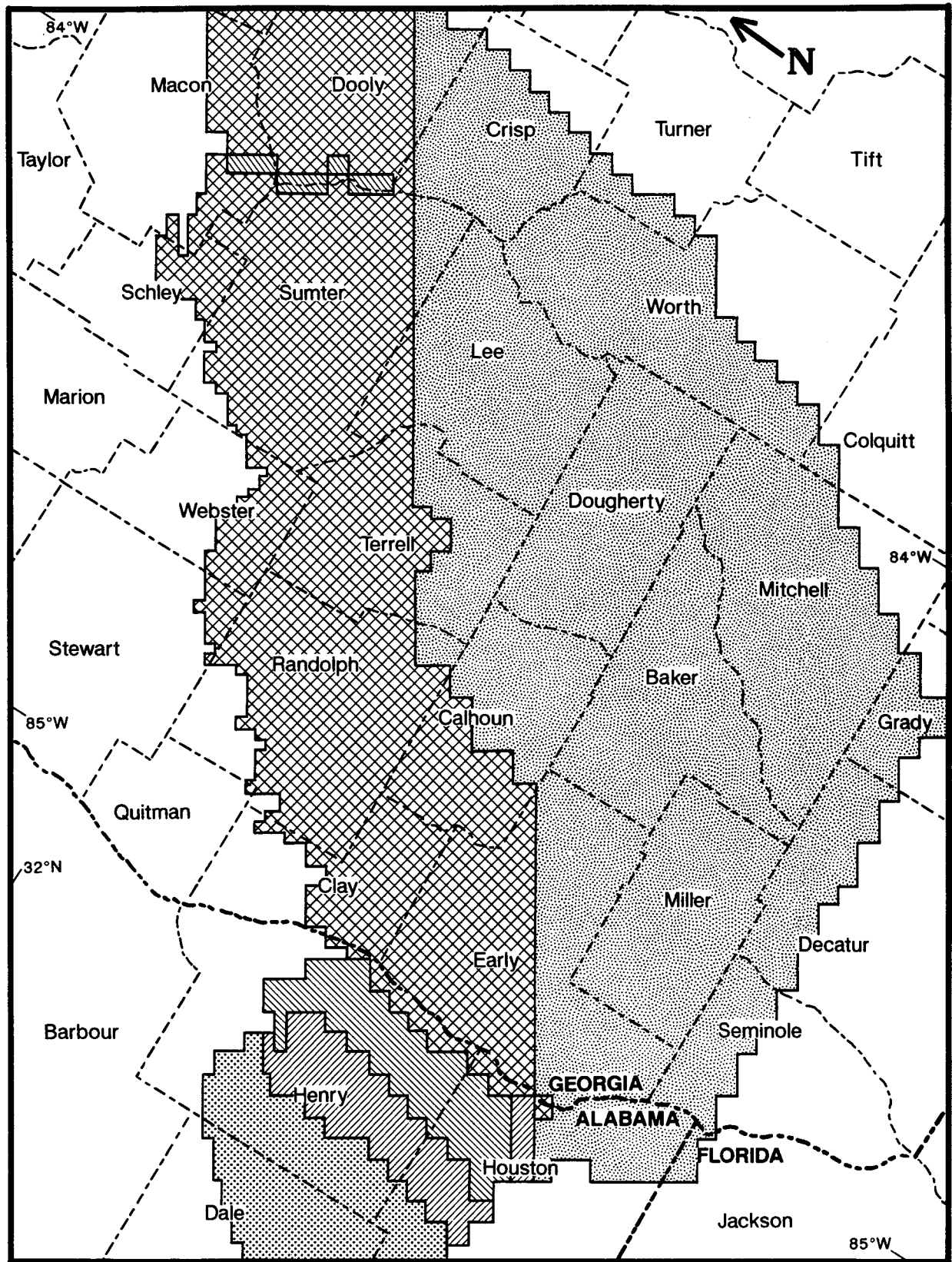
Figure II-11. Calibrated leakance for model layer C2.

84°W

Macon   Dooly

Taylor

Crisp   Turner

Tift

Schley   Sumter

Worth

Marion

Lee

Webster

Colquitt

Terrell   Dougherty

84°W

Stewart   Randolph

Mitchell

85°W

Calhoun   Baker

Grady

Quitman

32°N

Clay   Miller

Decatur

Early

Barbour   Seminole

GEORGIA

Henry   ALABAMA

FLORIDA

Houston

Dale   Jackson

85°W

N

| 0 | 10 | 20 | 30 | 40 miles |

5.8^{-11}sec^{-1} 1.2^{-11}sec^{-1}
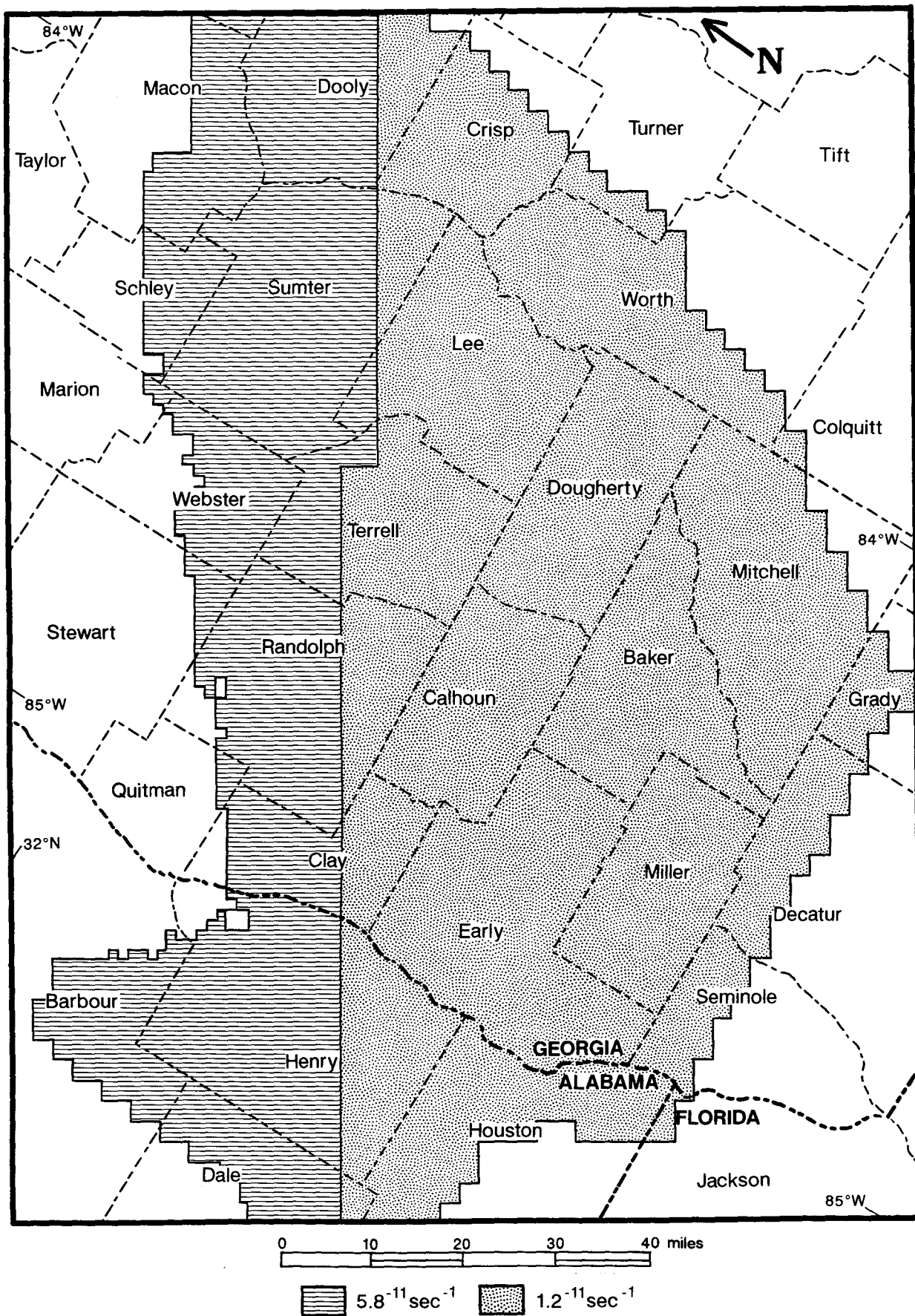
Figure II-12. Calibrated leakance for model layer C3.
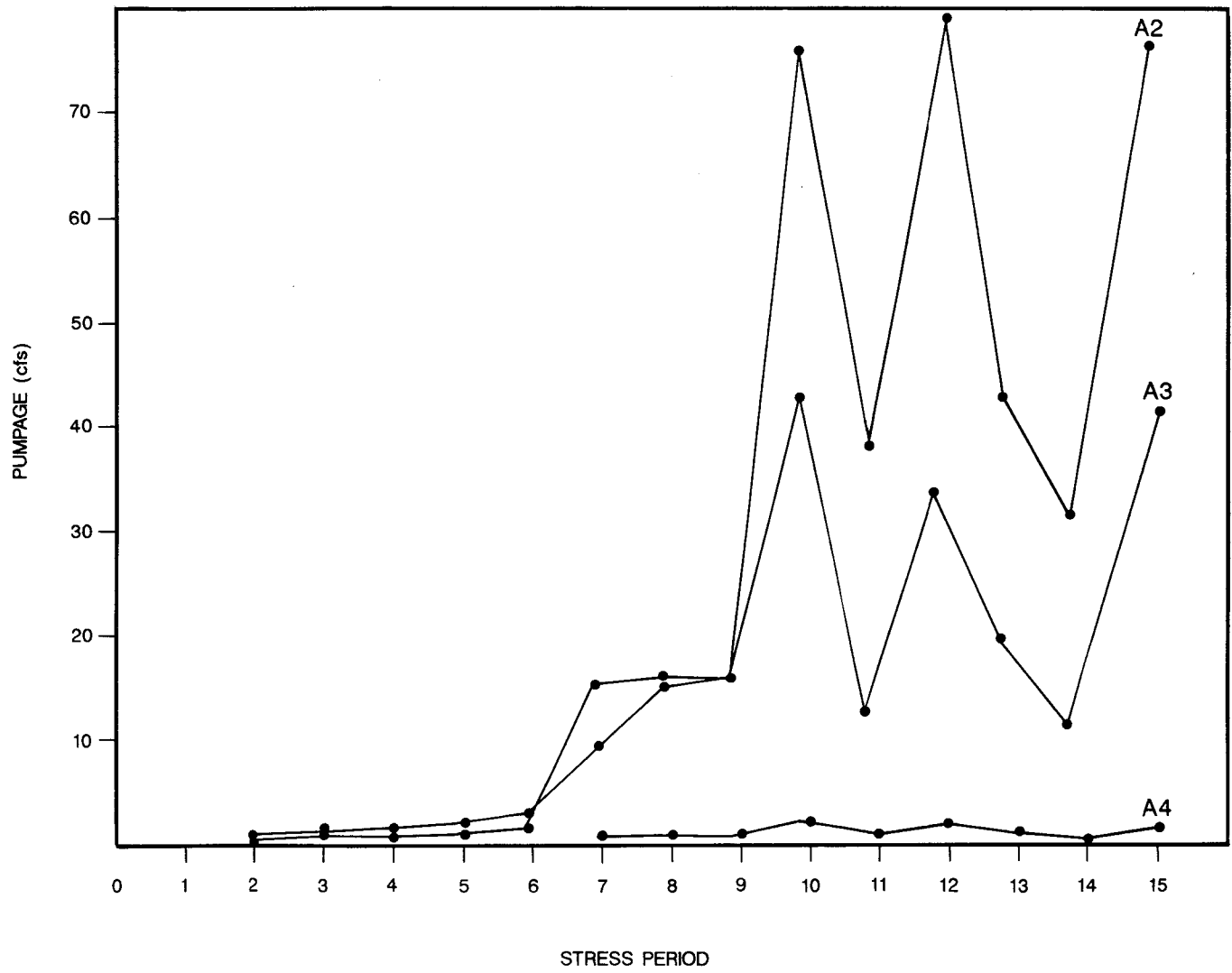
Figure II-13. Simulated irrigation pumpage.
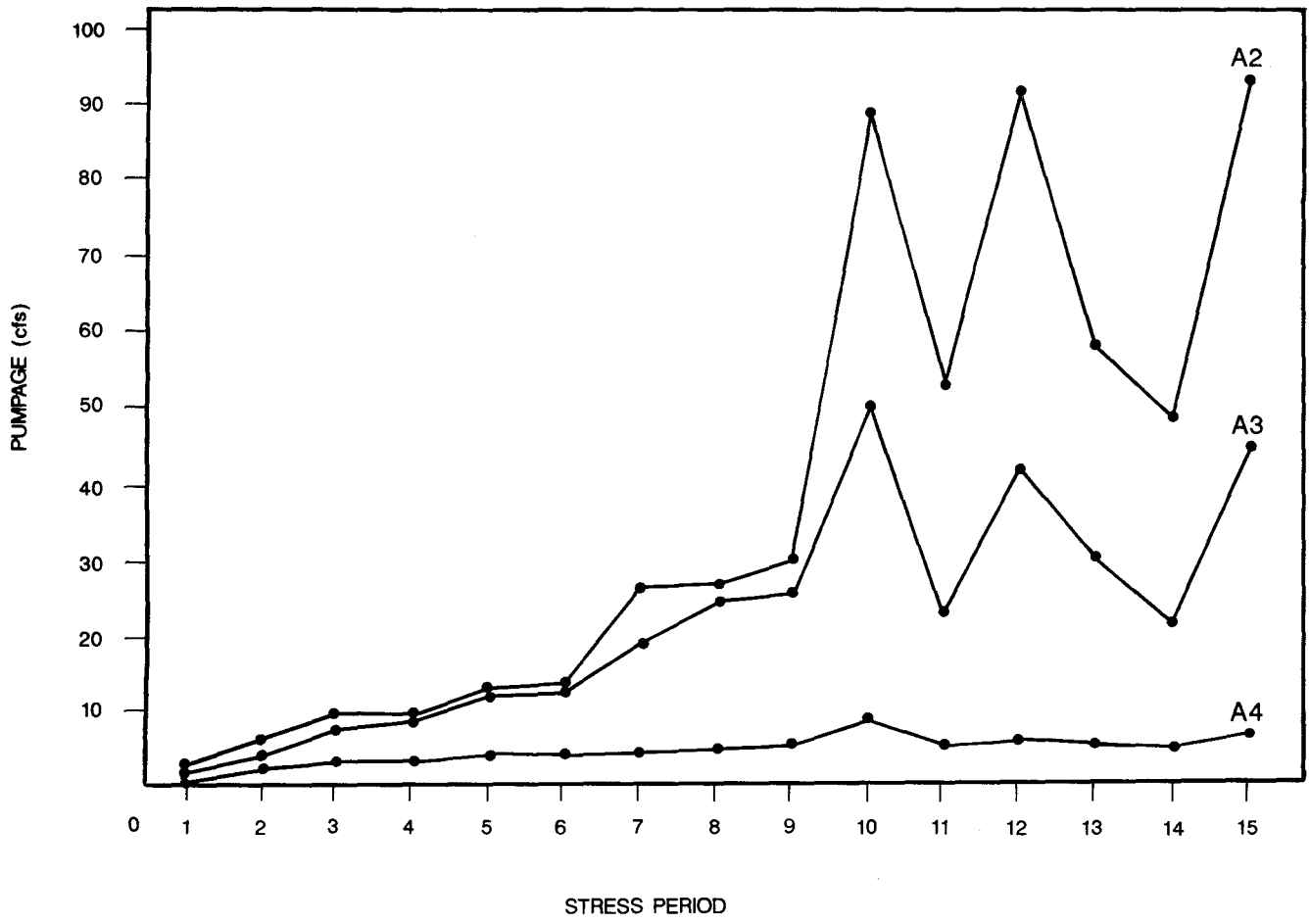
Figure II-14. Simulated pumpage for all uses.
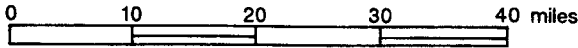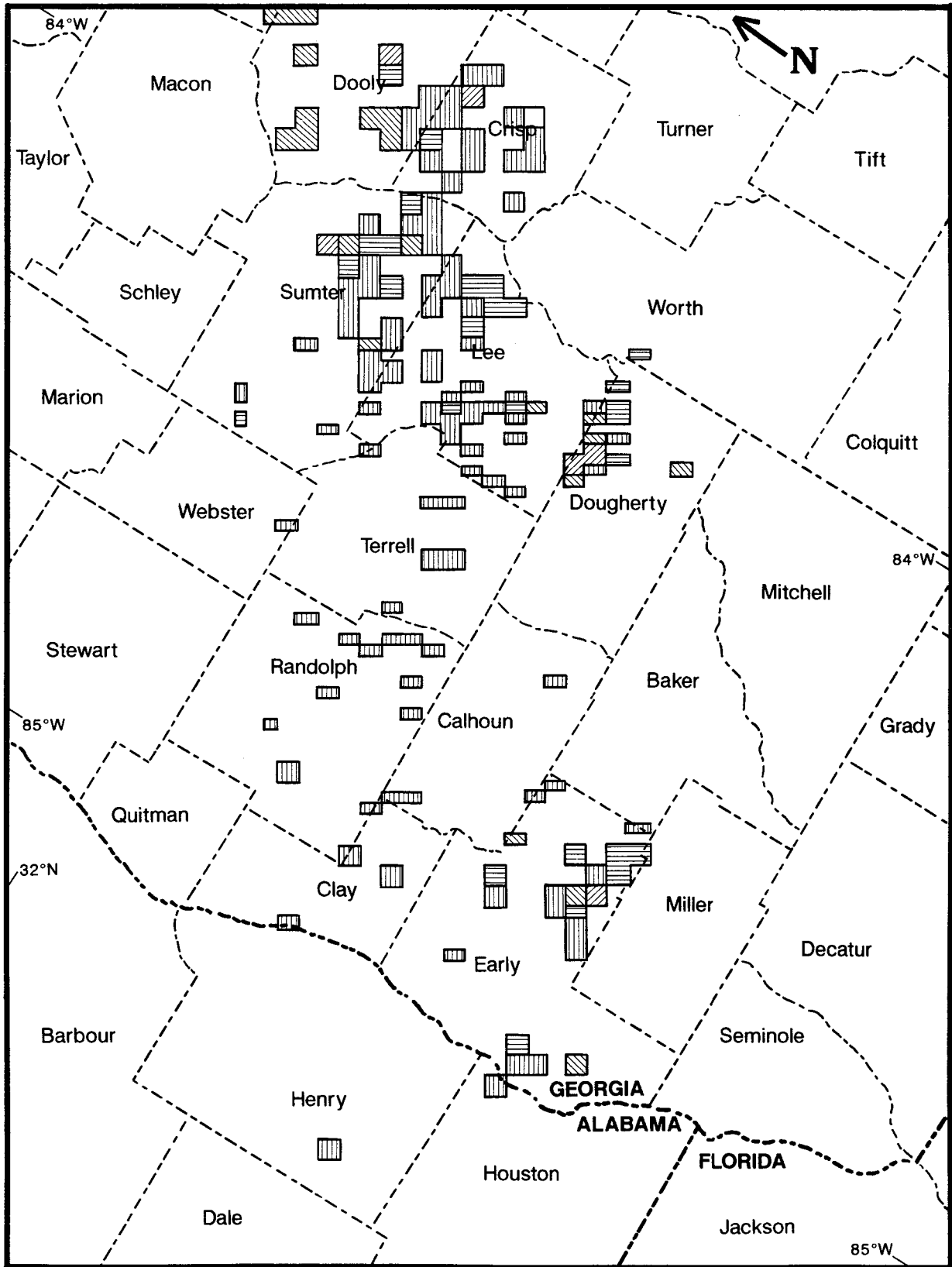
Figure II-15. Simulated pumpage from model layer A2 in stress period 15. Pumpage is in cubic feet per second.
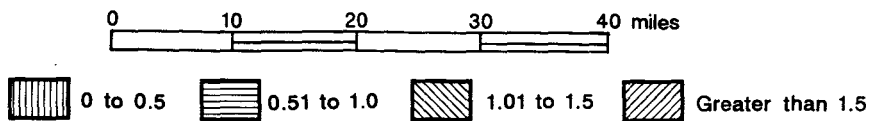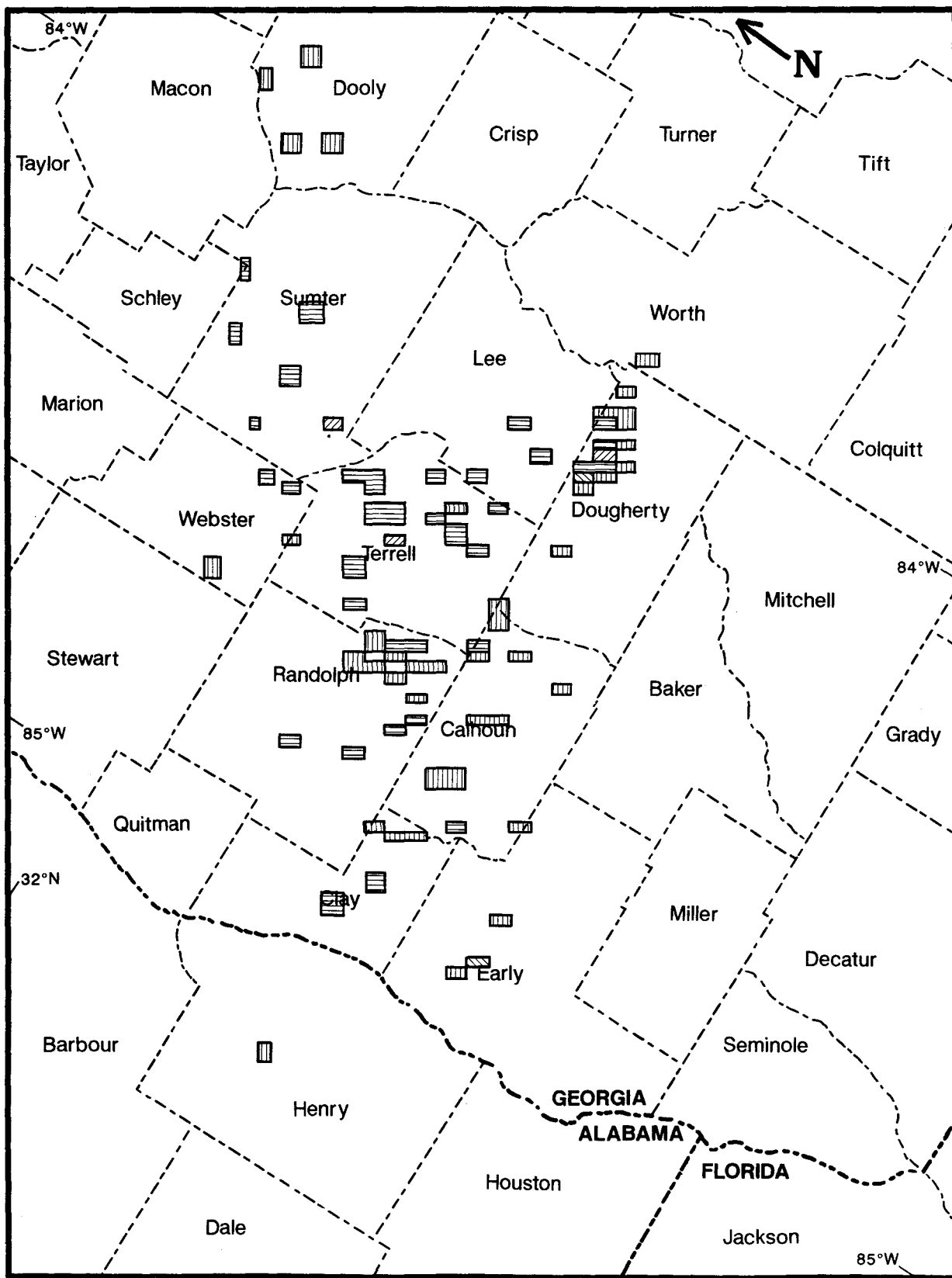
Figure II-16. Simulated pumpage from model layer A3 in stress period 15. Pumpage is in cubic feet per second.
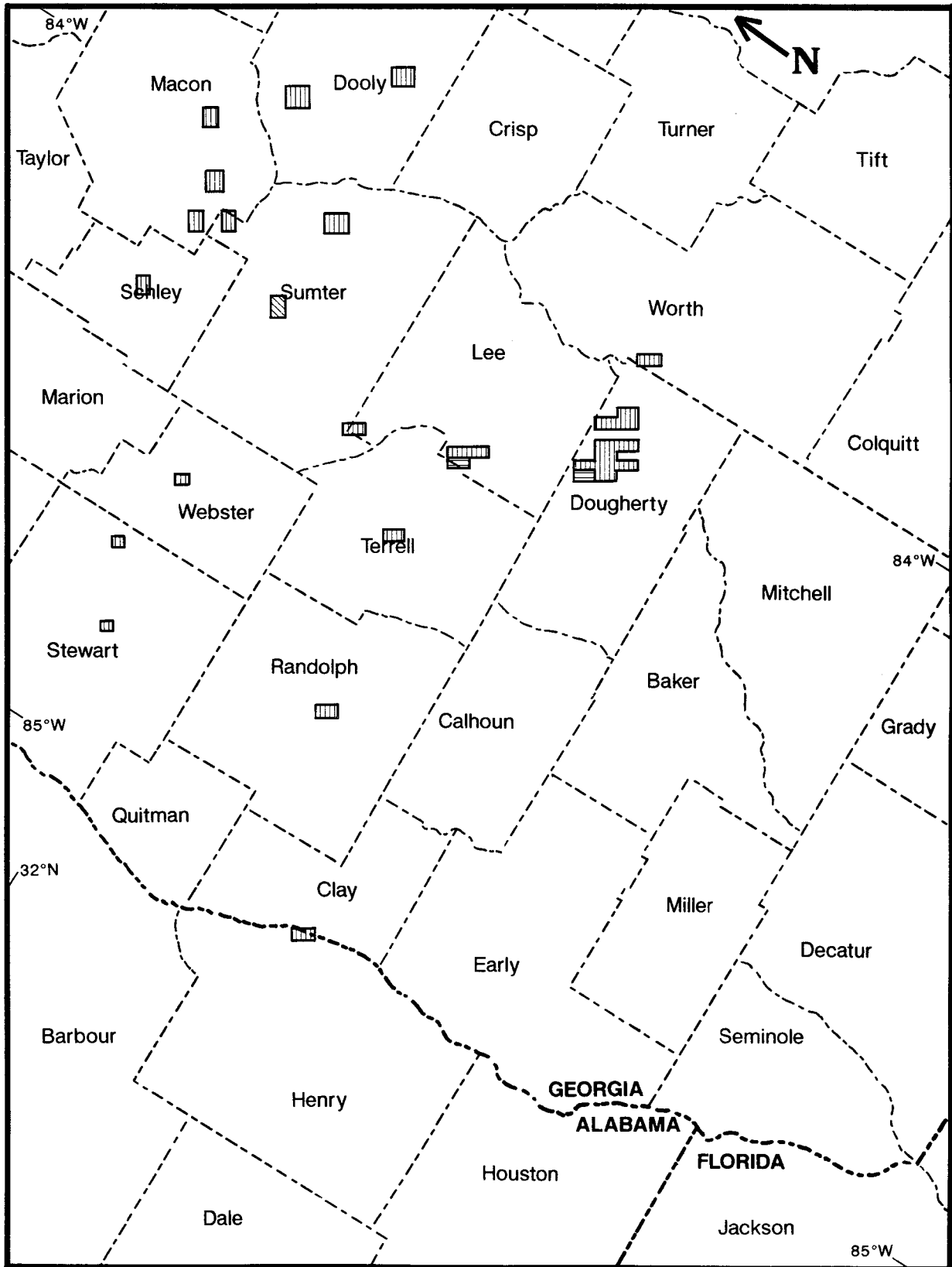
Figure II-17. Simulated pumpage from model layer A4 in stress period 15. Pumpage is in cubic feet per second.
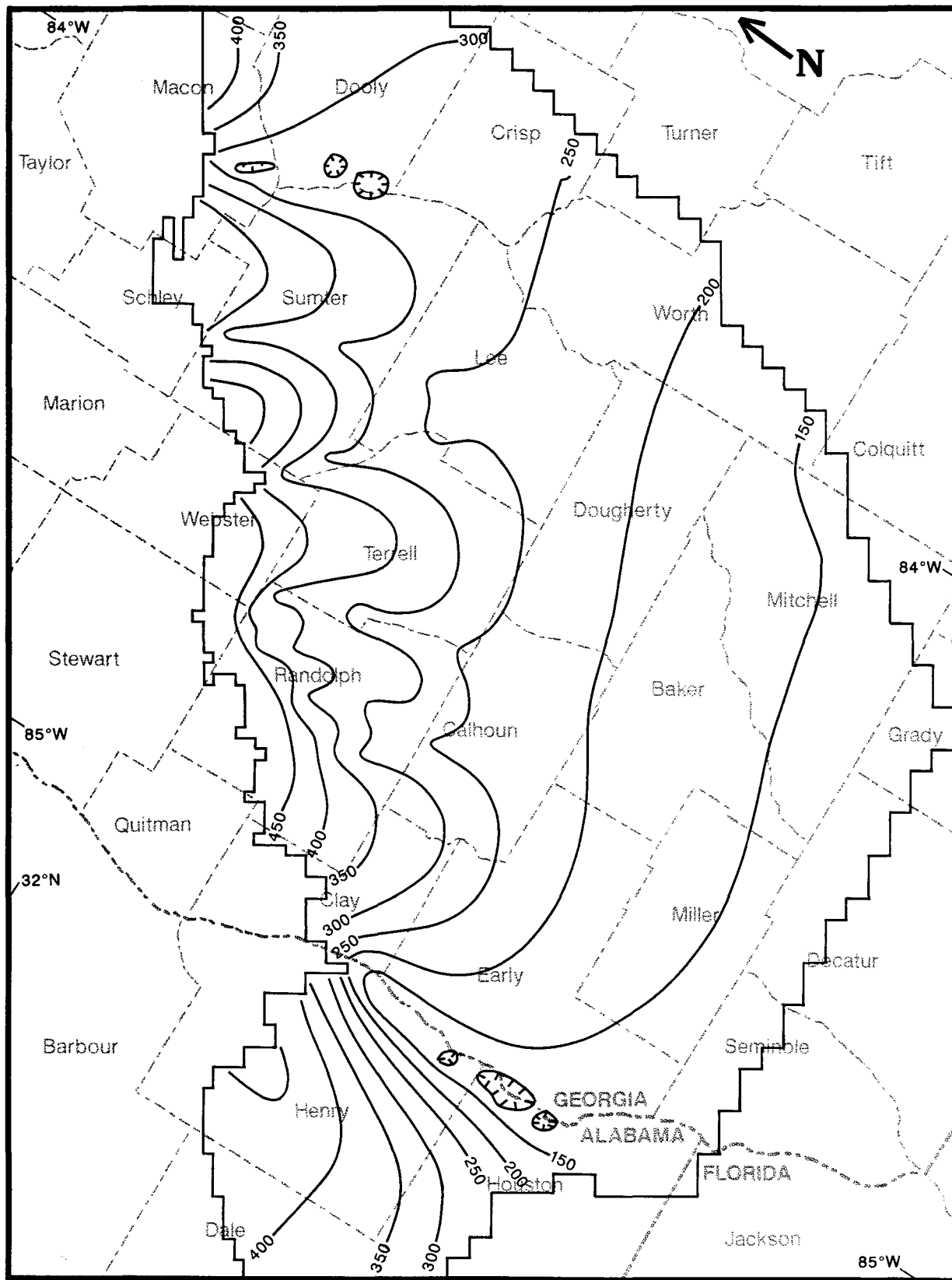
Figure II-18. Steady-state simulated potentiometric surface for model layer A2.
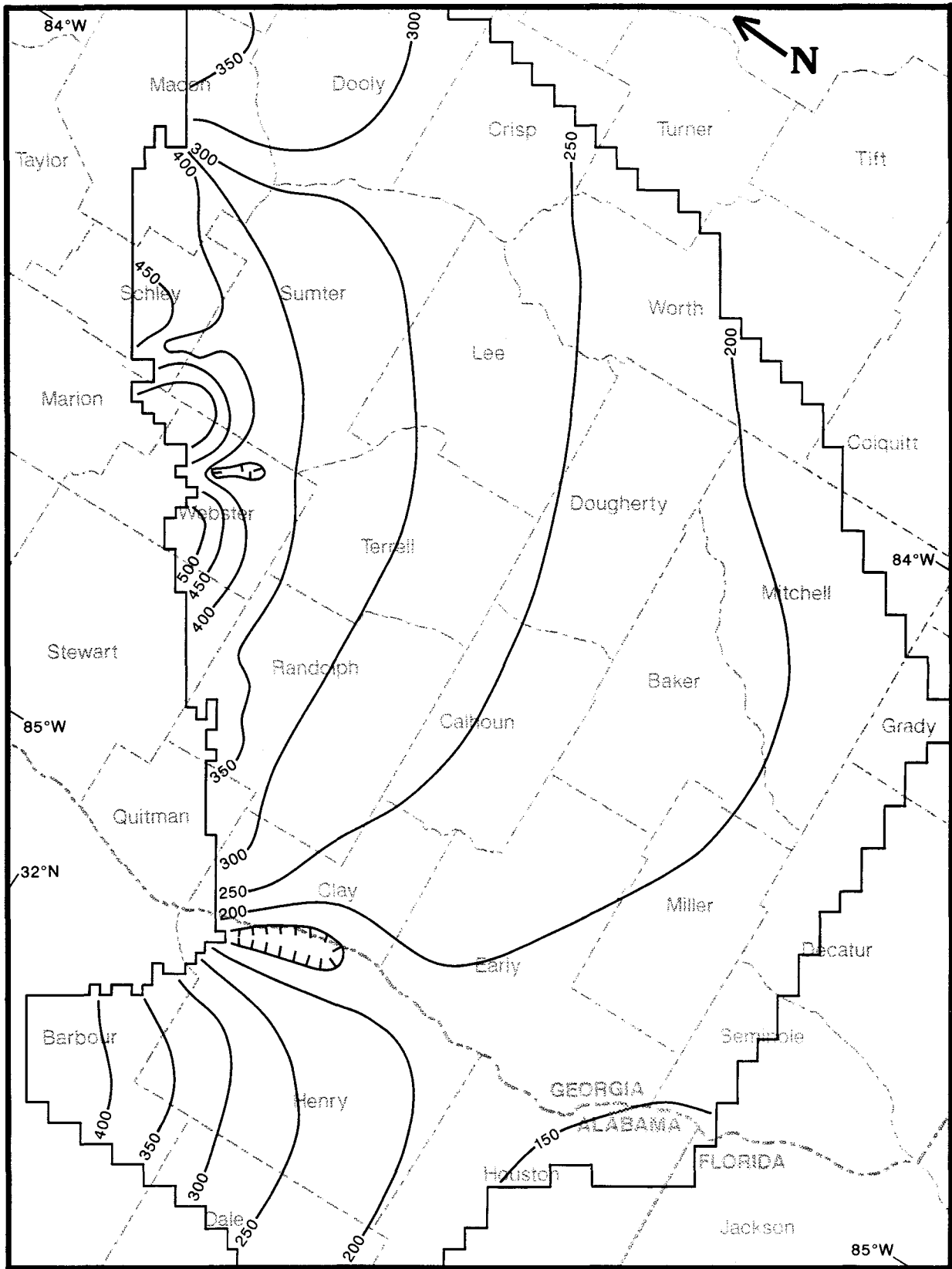
Figure II-19. Steady-state simulated potentiometric surface for model layer A3.
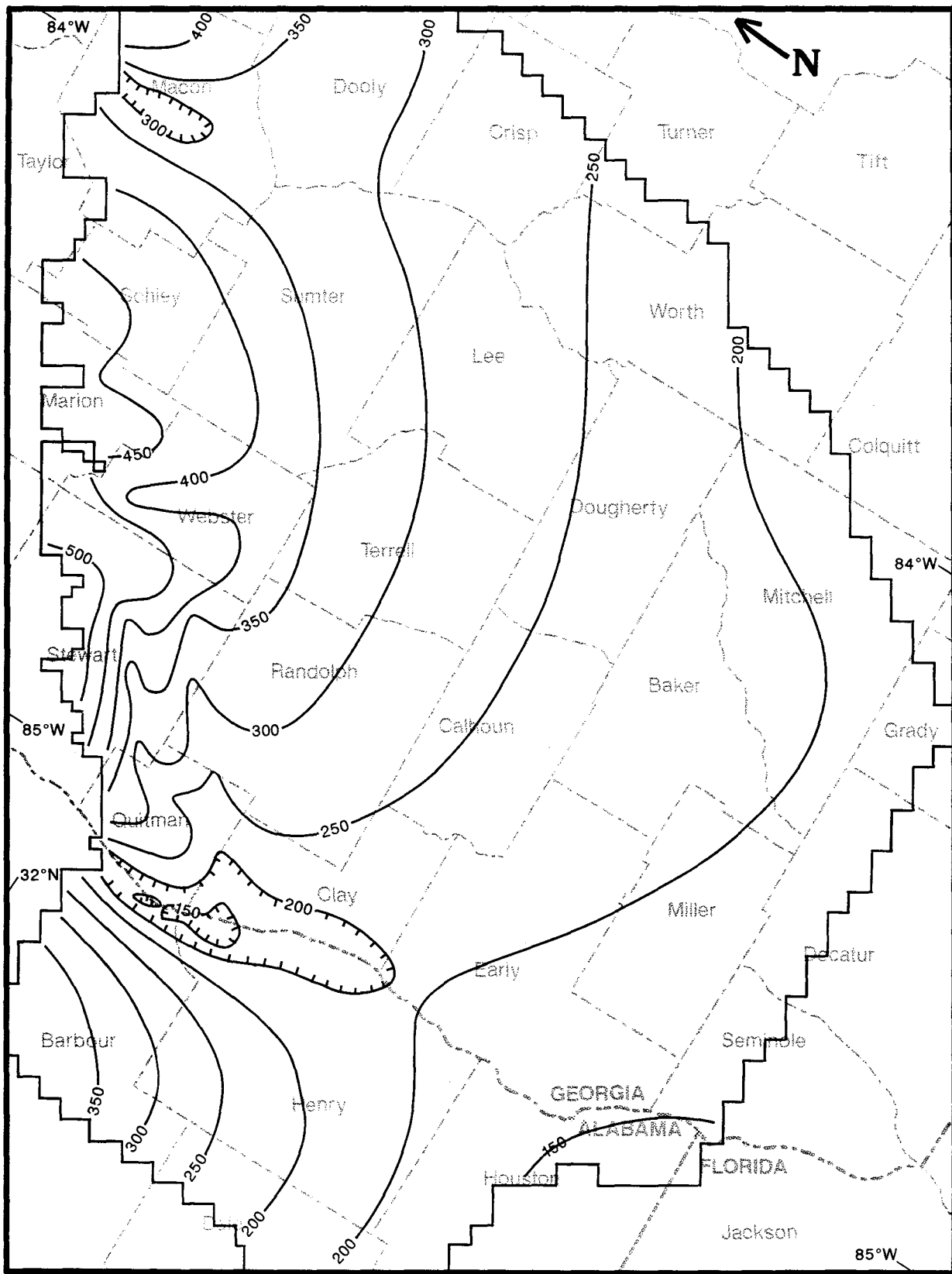
Figure II-20. Steady-state simulated potentiometric surface for model layer A4.
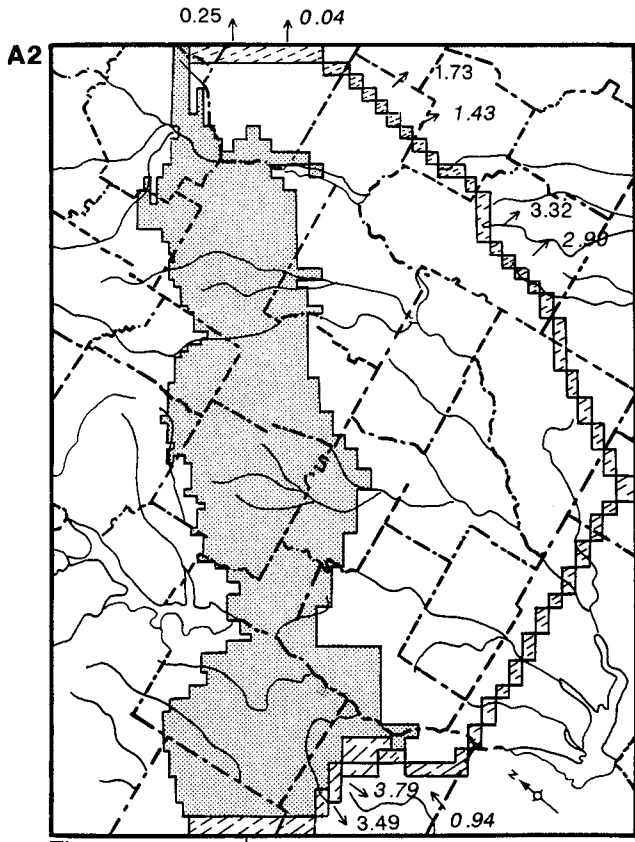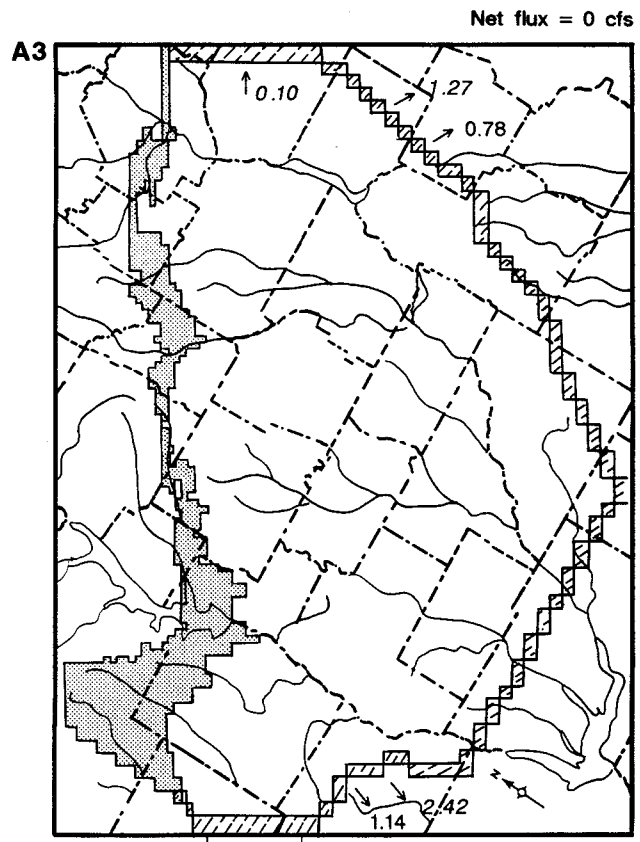
Note: where two values are present,
estimated is on the left and simulated
is on the right. Where one value is
present, this is simulated.
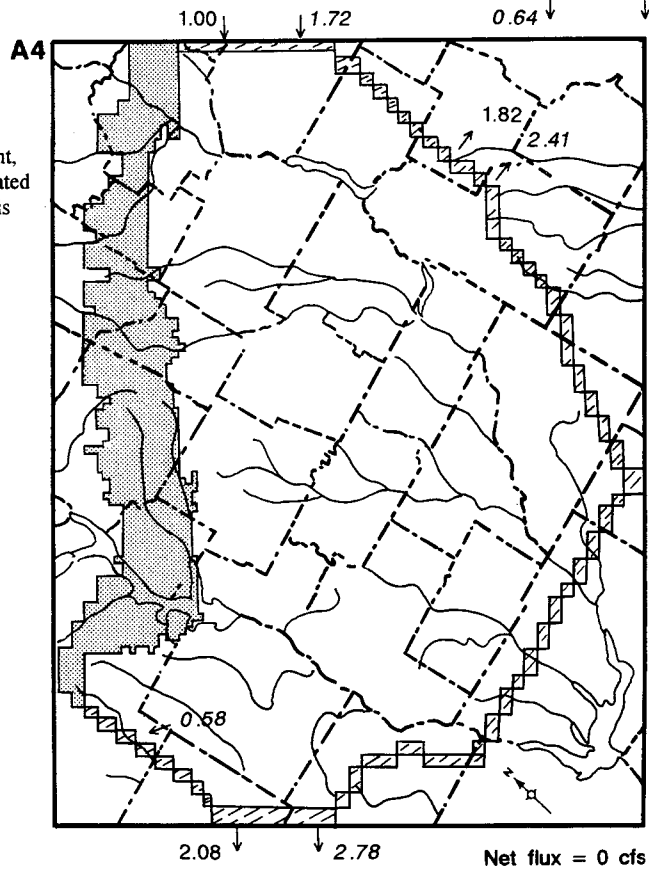
Figure II-21. Estimated and simulated fluxes for model layer A2, model layer A3, and model layer A4.

A2

2.3 1.6

0 ←

0.3 →

2.1 11.0

← 0

→ 9.6

Dip →

2.1 3.3

Recharge = 339
River Flux = 320.1

A3

0.1 0.4

0 ←

0.2 →

6.5 6.9

← 0

→ 2.1

Dip →

2.3 0

Recharge = 64
River Flux = 29.8

A4

2.2 0.5

0.1 ←

2.6 →

40.4 11.7

← 0

→ 3.4

Dip →

5.9 0.4

Recharge = 164
River Flux = 186.3
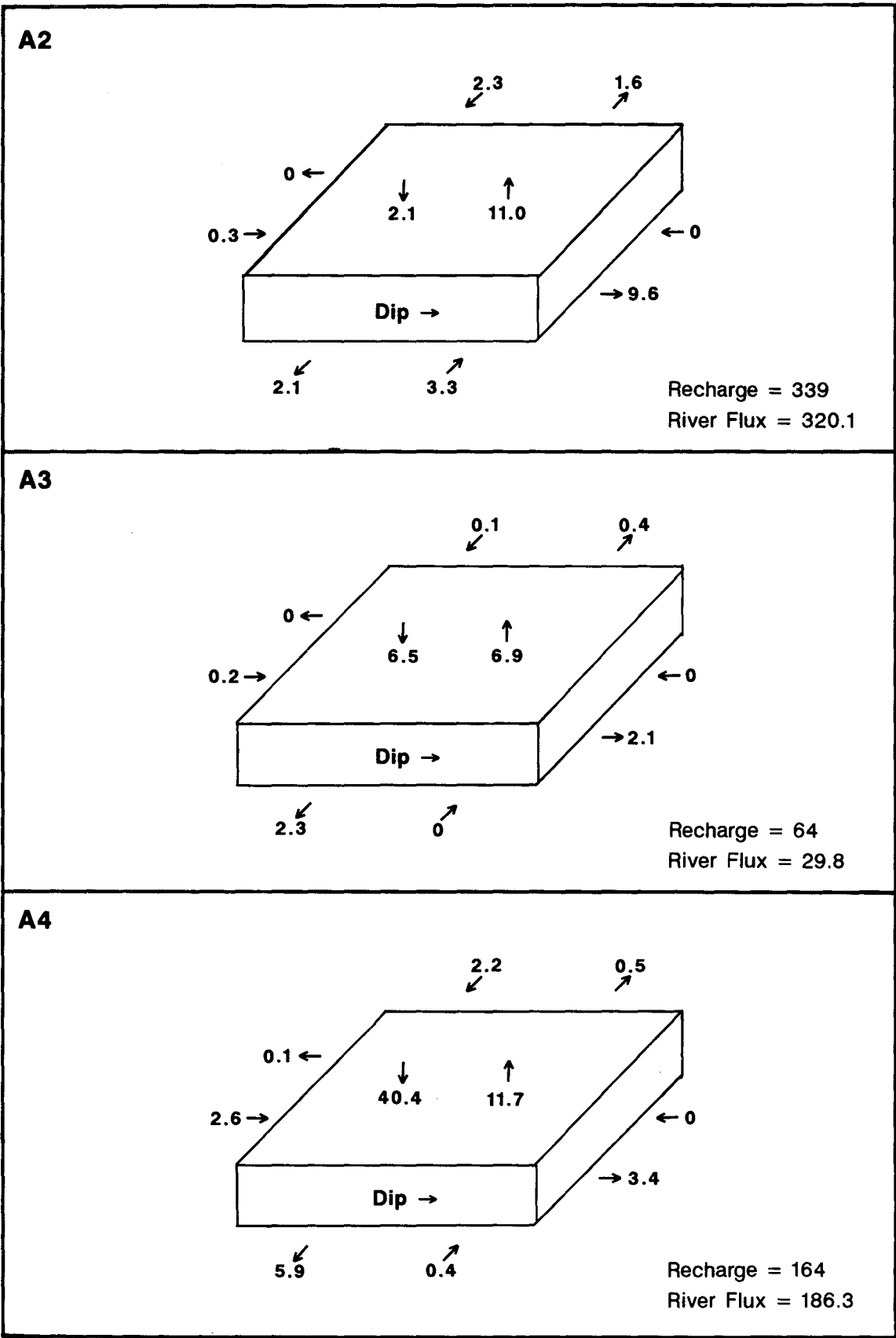
Figure II-22. Steady-state mode boundary fluxes for recharge, discharge, and leakance. All values are in cubic feet per second.
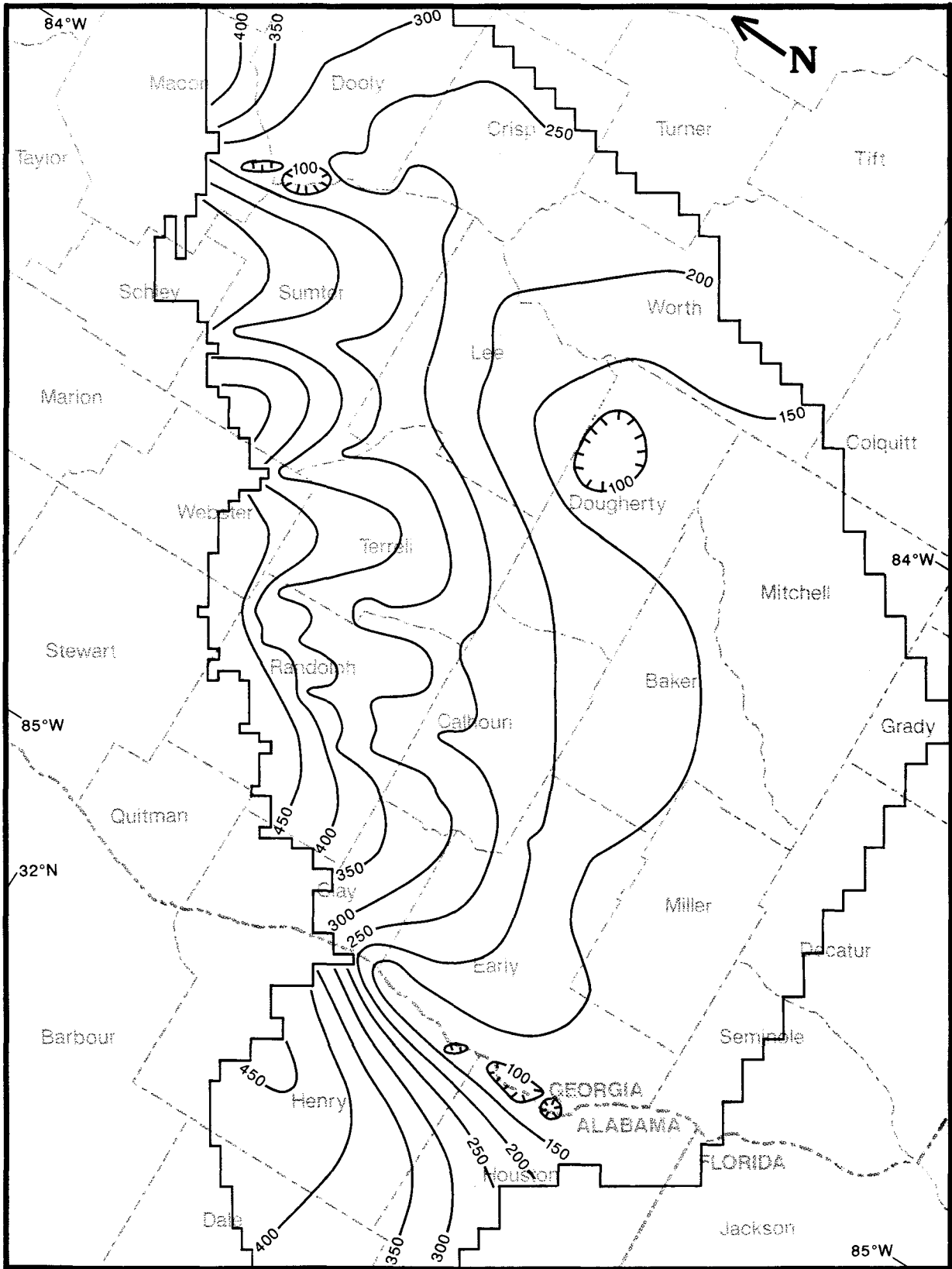
Figure II-23. Simulated potentiometric surface for model layer A2 at the end of stress period 15.
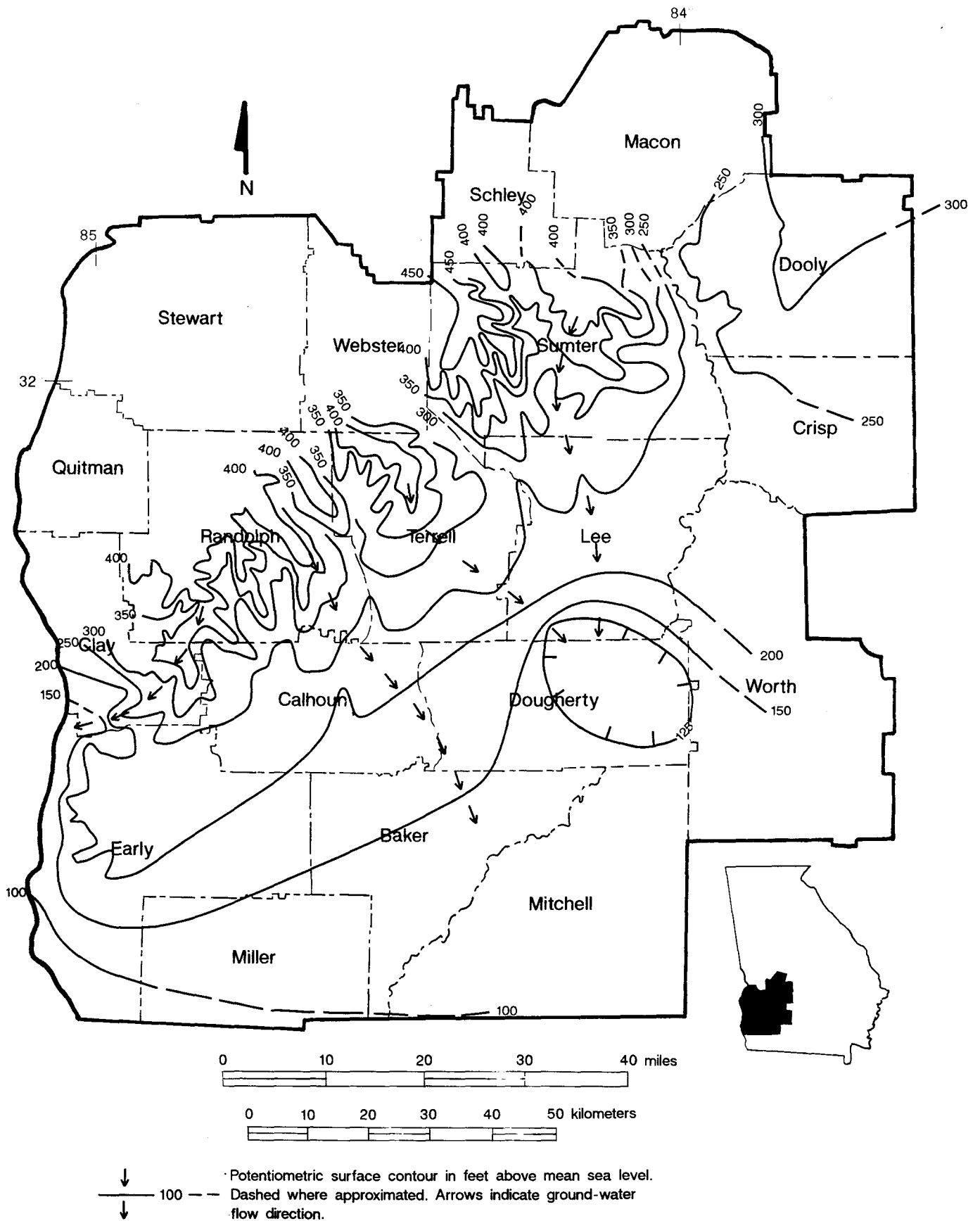
Figure II-24. 1986 potentiometric surface for the Claiborne aquifer (model layer A2).
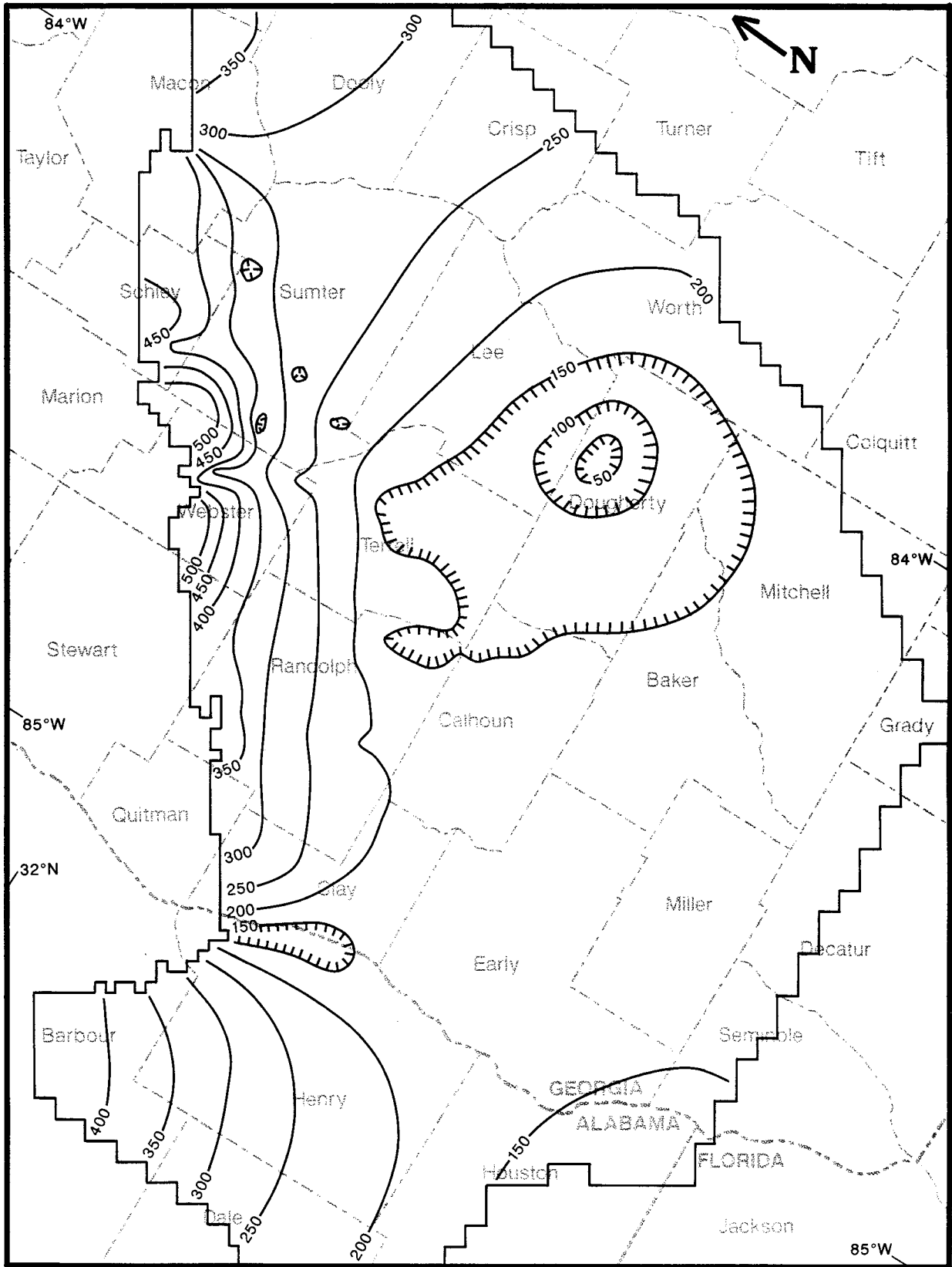
Figure II-25. Simulated potentiometric surface for model layer A3 at the end of stress period 15.
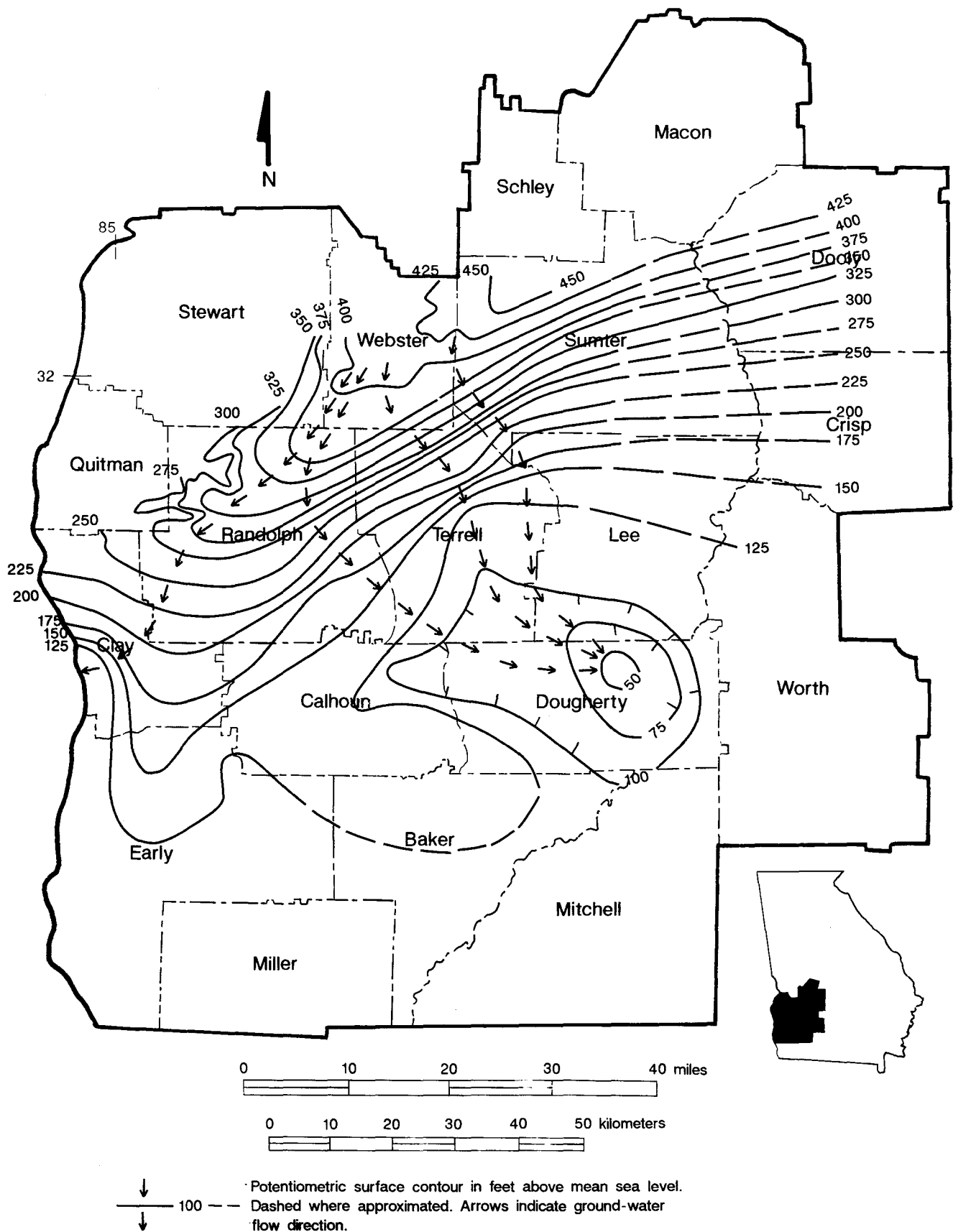
Figure II-26. 1986 potentiometric surface for the Clayton aquifer (model layer A3).
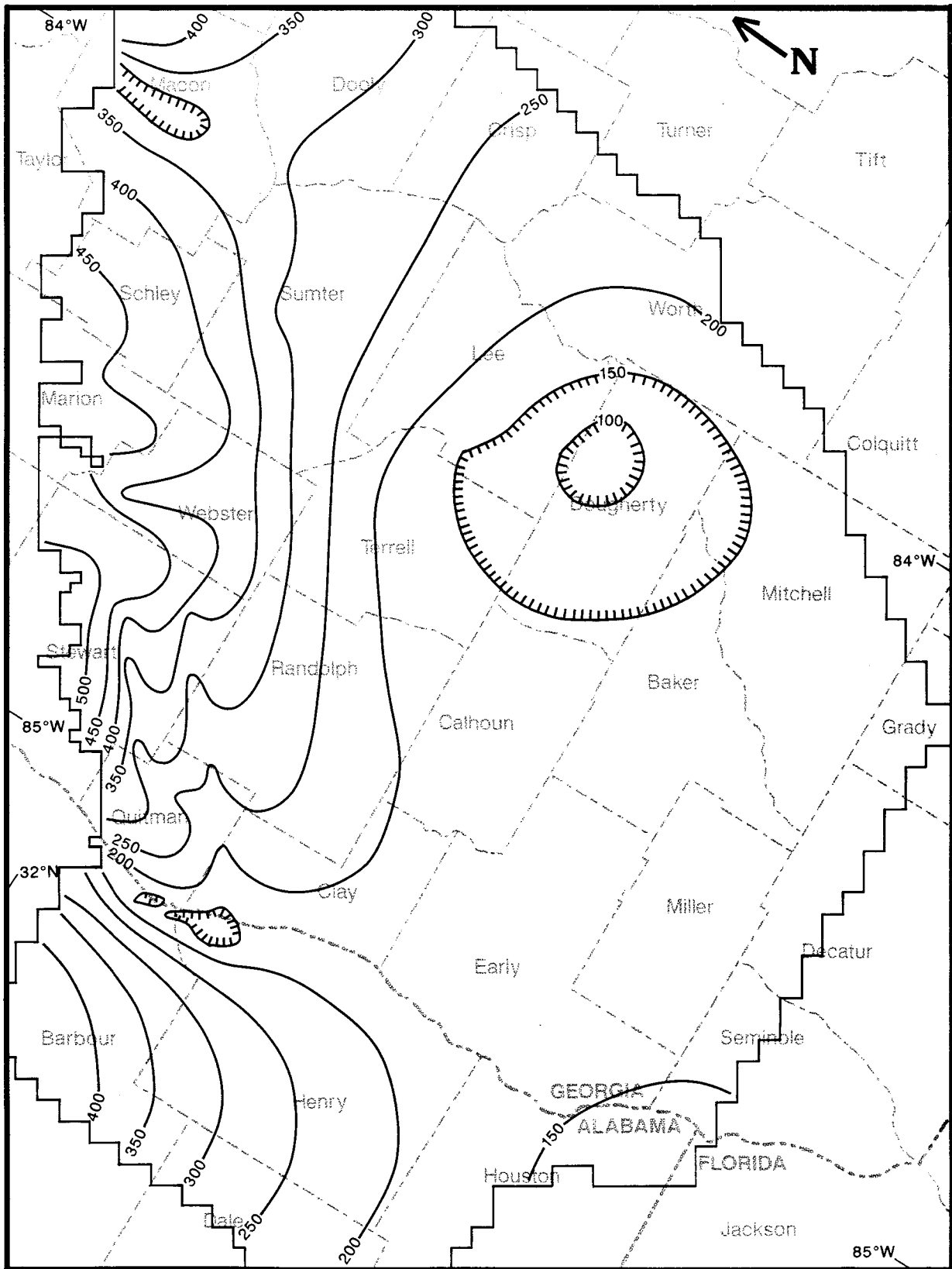
Figure II-27. Simulated potentiometric surface for model layer A4 at the end of stress period 15.
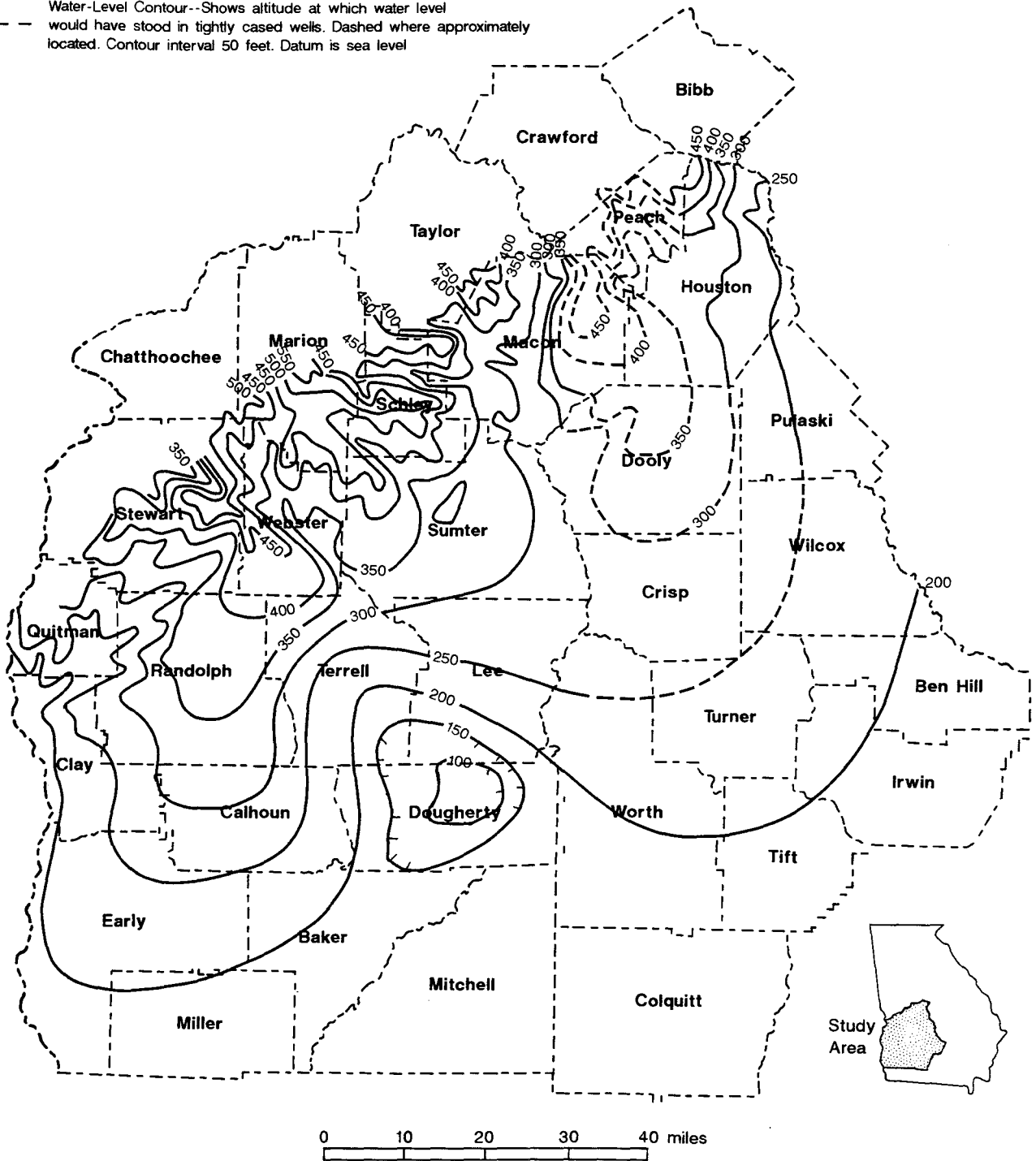
Figure II-28. 1986 potentiometric surface for the Providence aquifer (model layer A4).
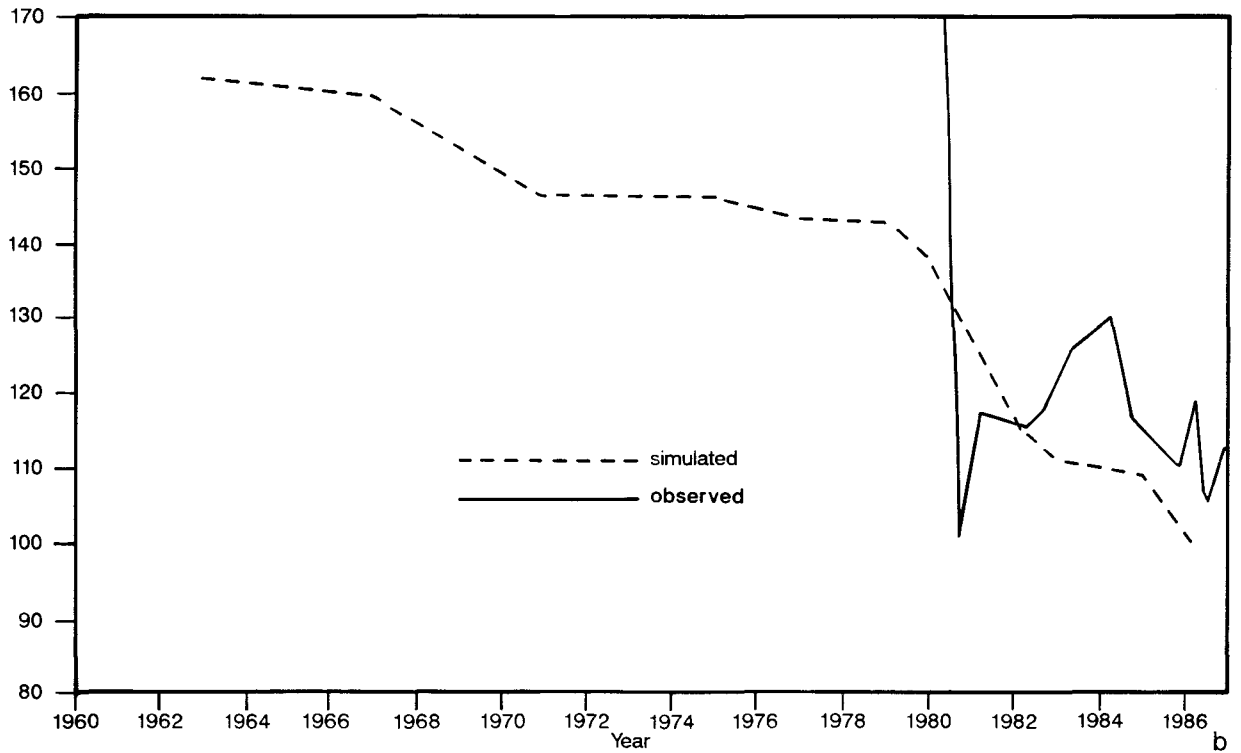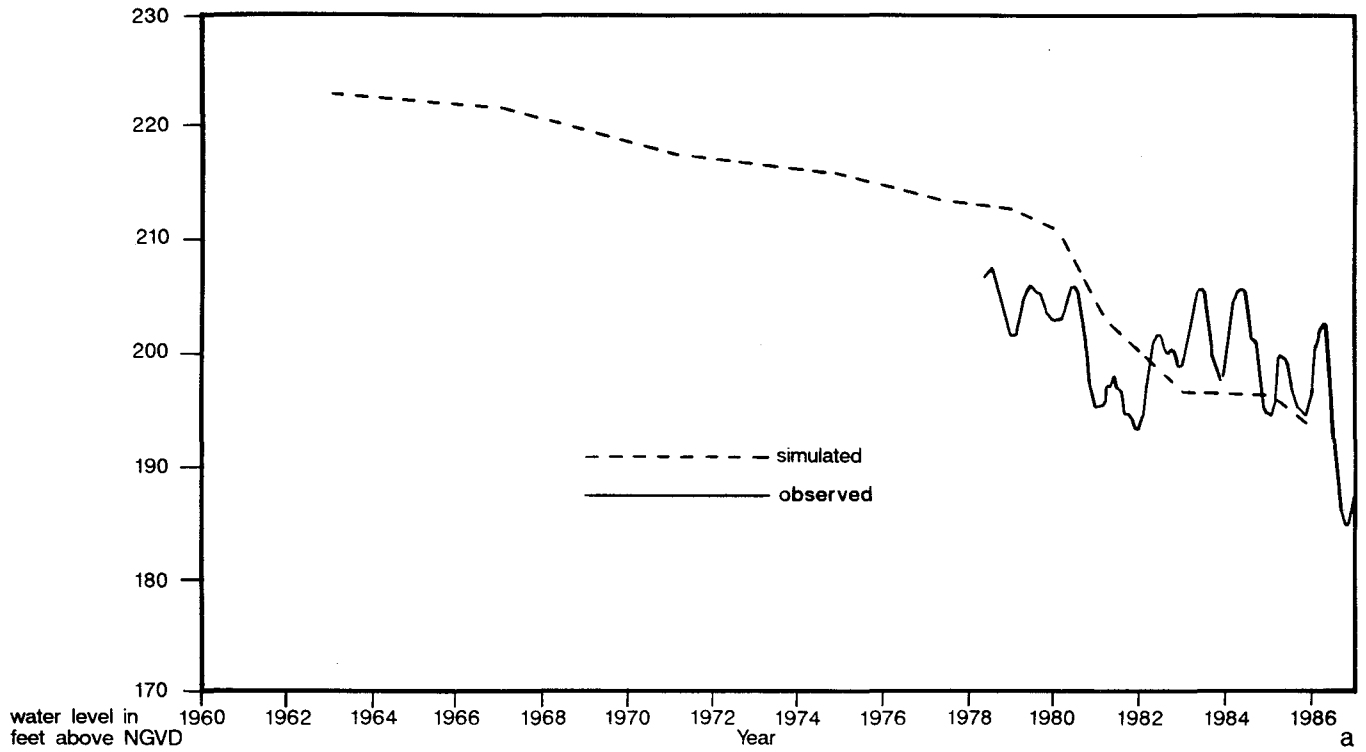
Figure II-29. Simulated and observed heads at (a) USGS test well 4, Claiborne aquifer, Doughterty County and (b) USGS test well 2, Claiborne aquifer, Dougherty County.
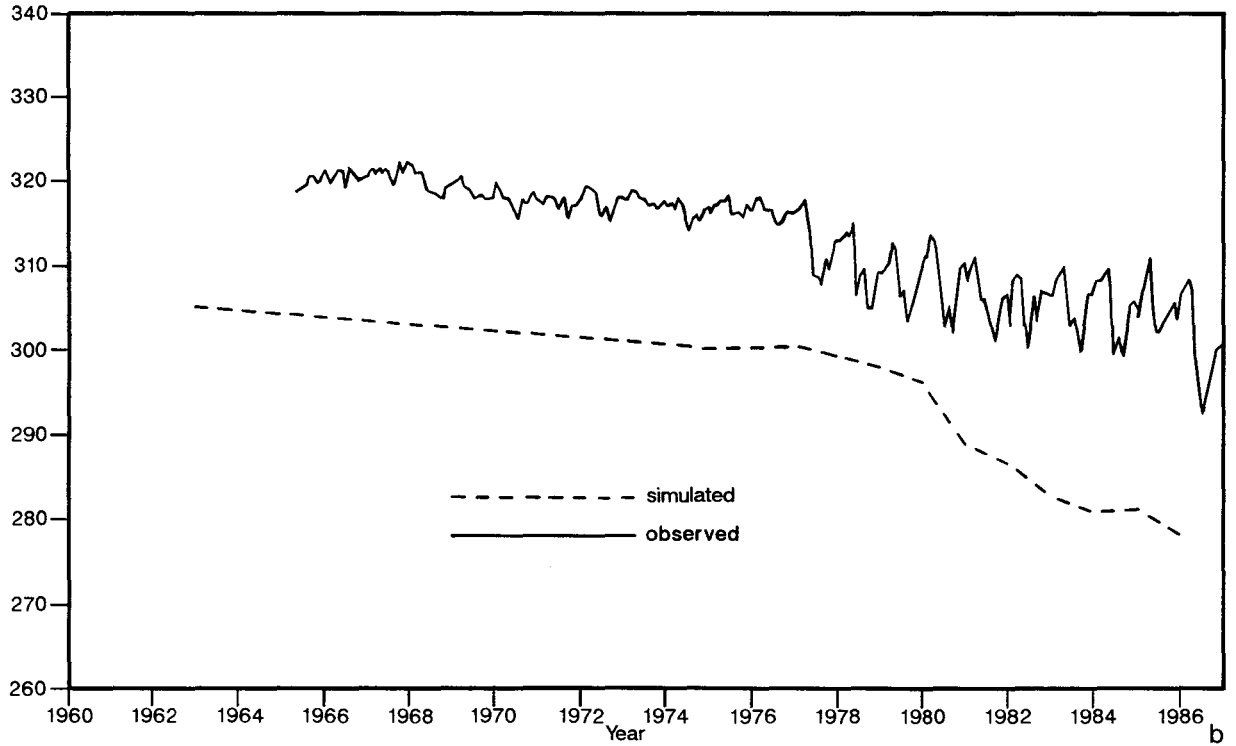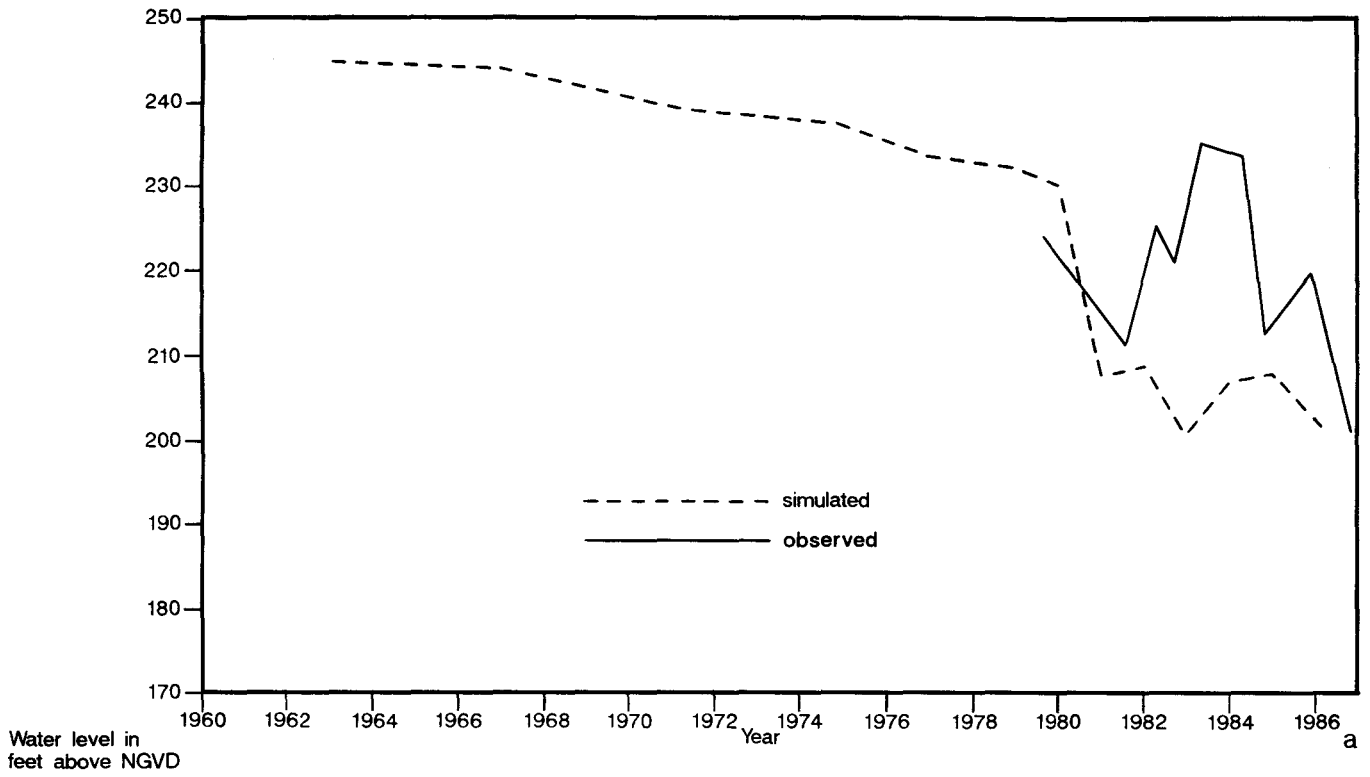
Figure II-30. Simulated and observed heads at (a) W.H. Fryer well, Claiborne aquifer, Lee County and (b) Cuthbert well, Clayton aquifer, Randolph County.
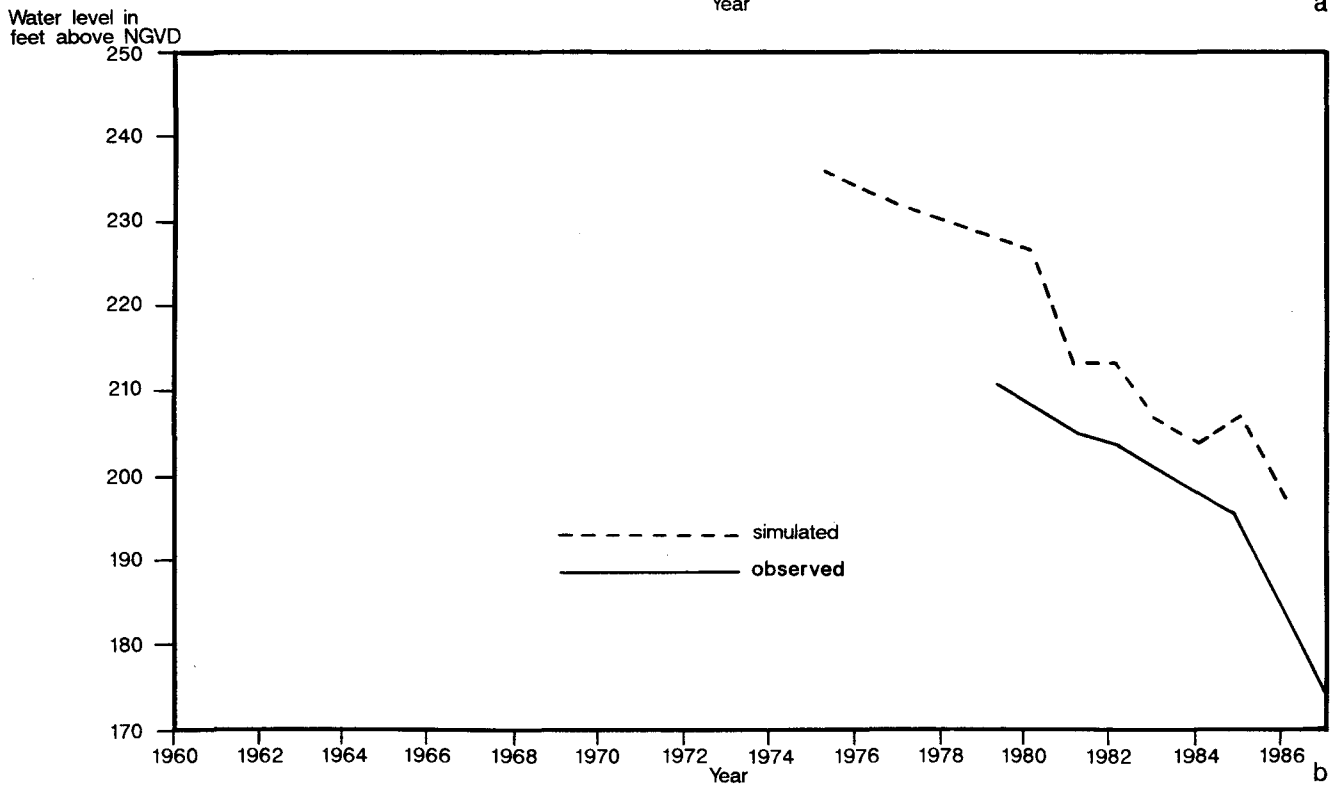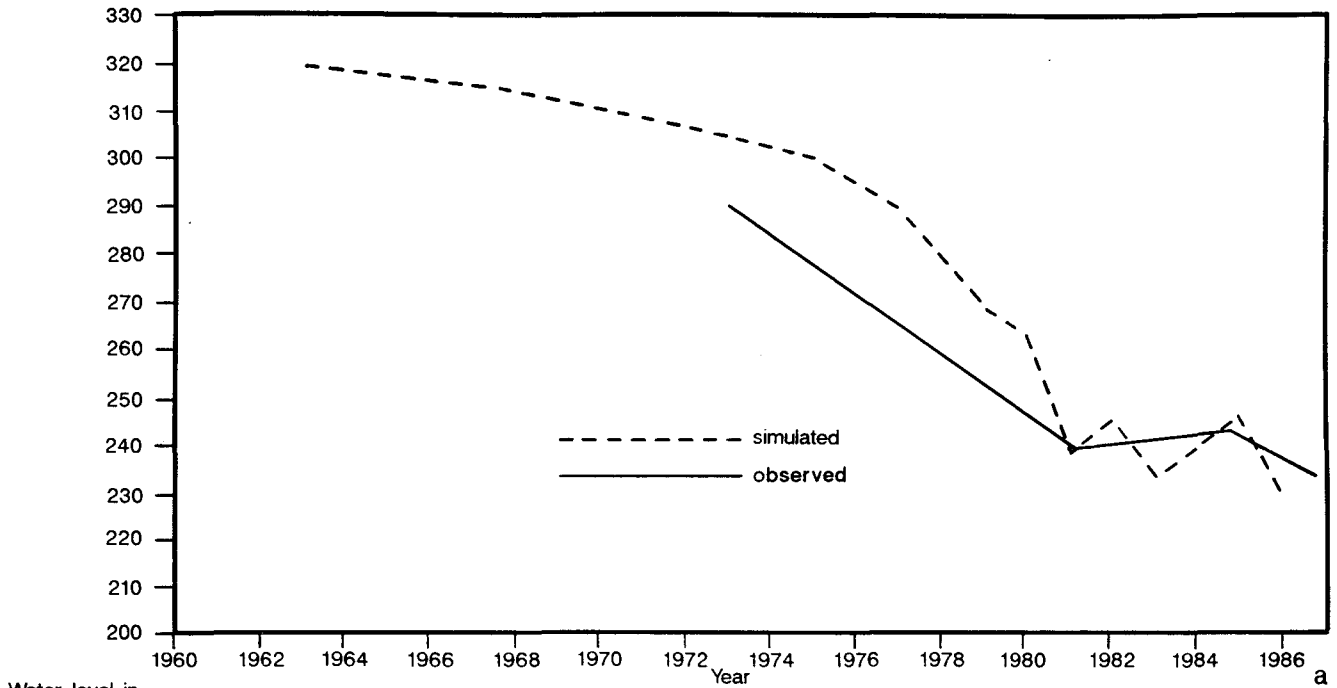
Figure II-31. Simulated and observed heads at (a) Don Foster well, Clayton aquifer, Terrell County and (b) H.T. McLendon #1 well, Clayton aquifer, Calhoun County.
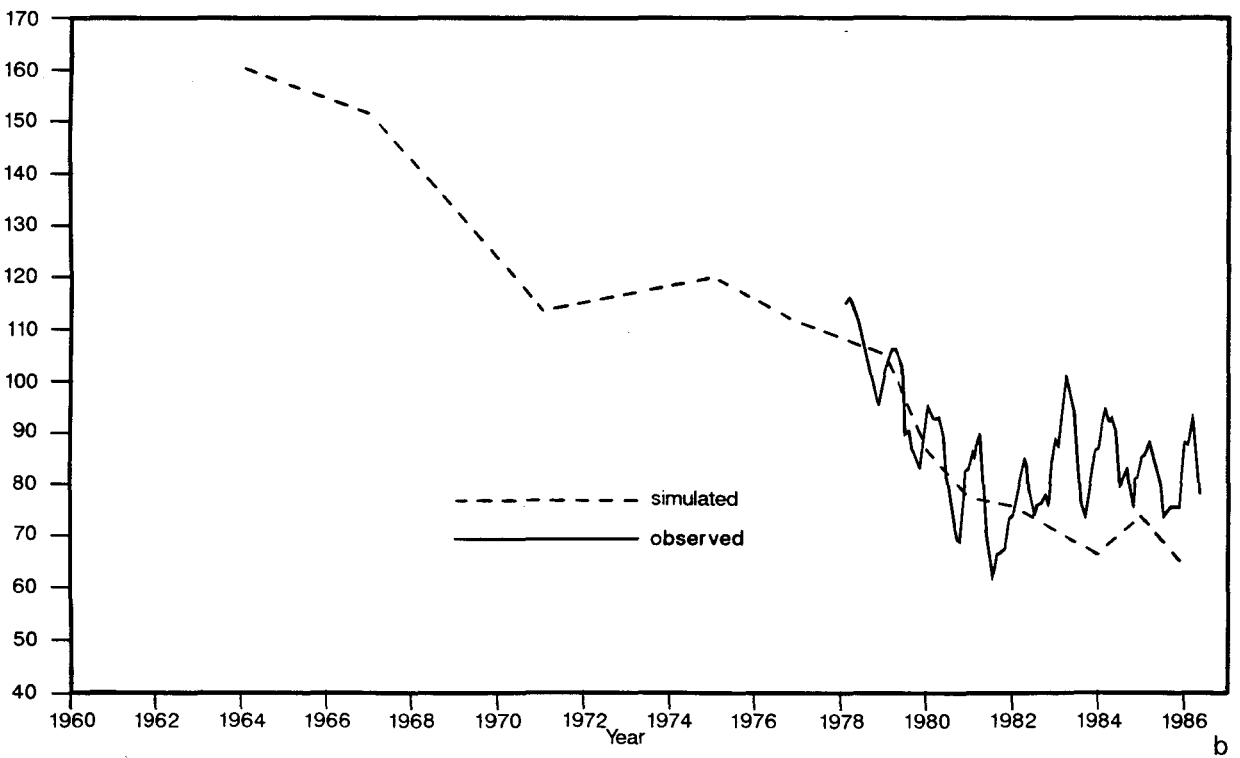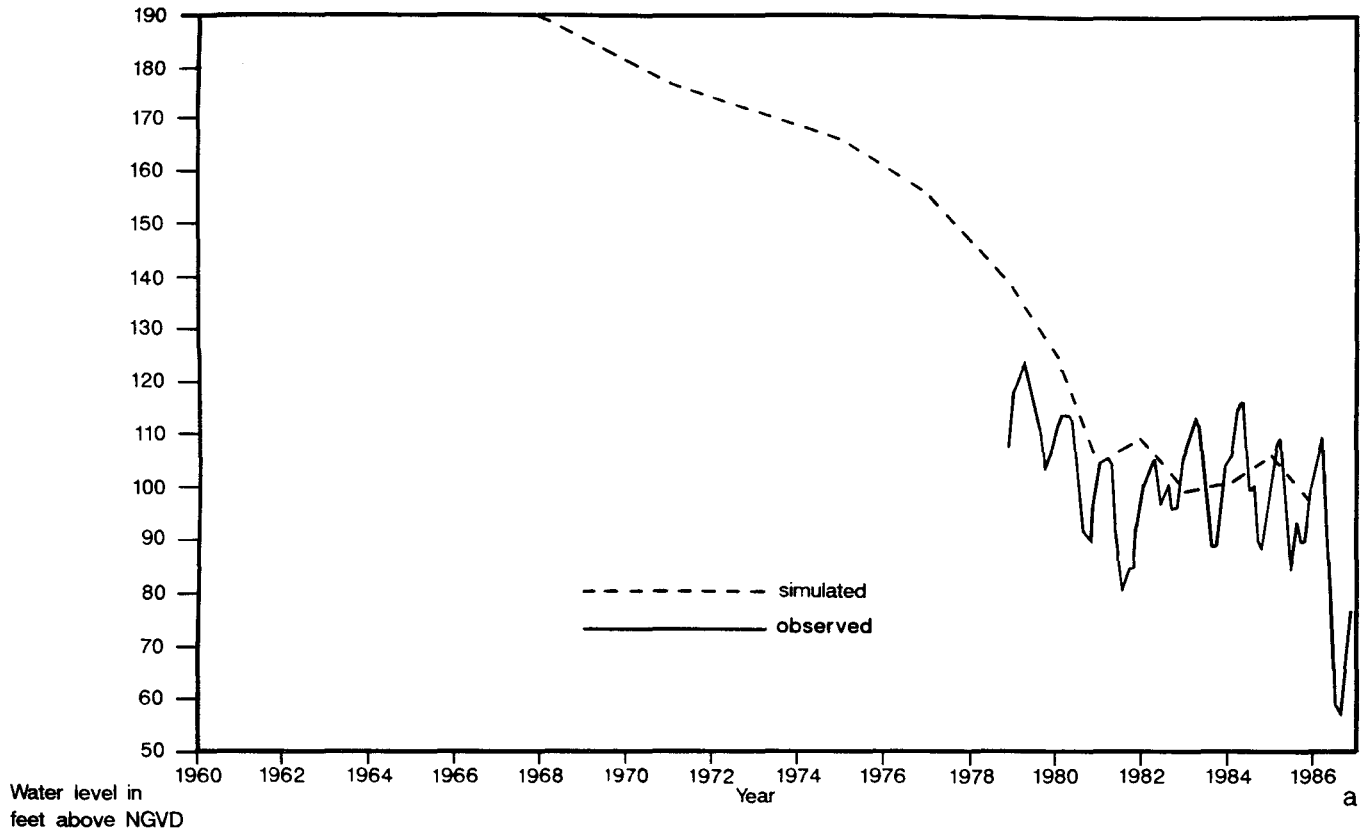
Figure II-32. Simulated and observed heads at (a) USGS test well 9, Clayton aquifer, Lee County and (b) Turner City well 2, Clayton aquifer, Dougherty County.
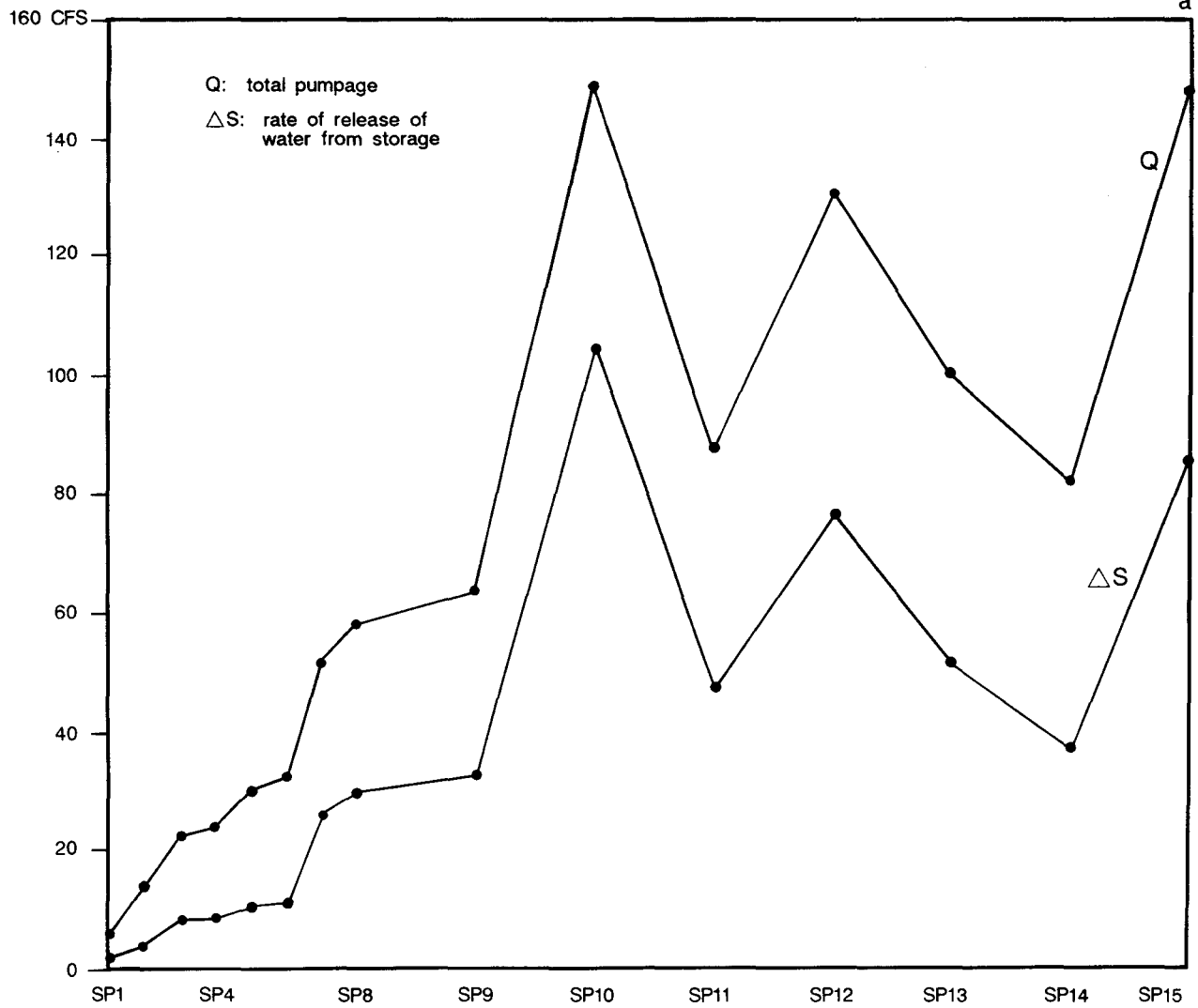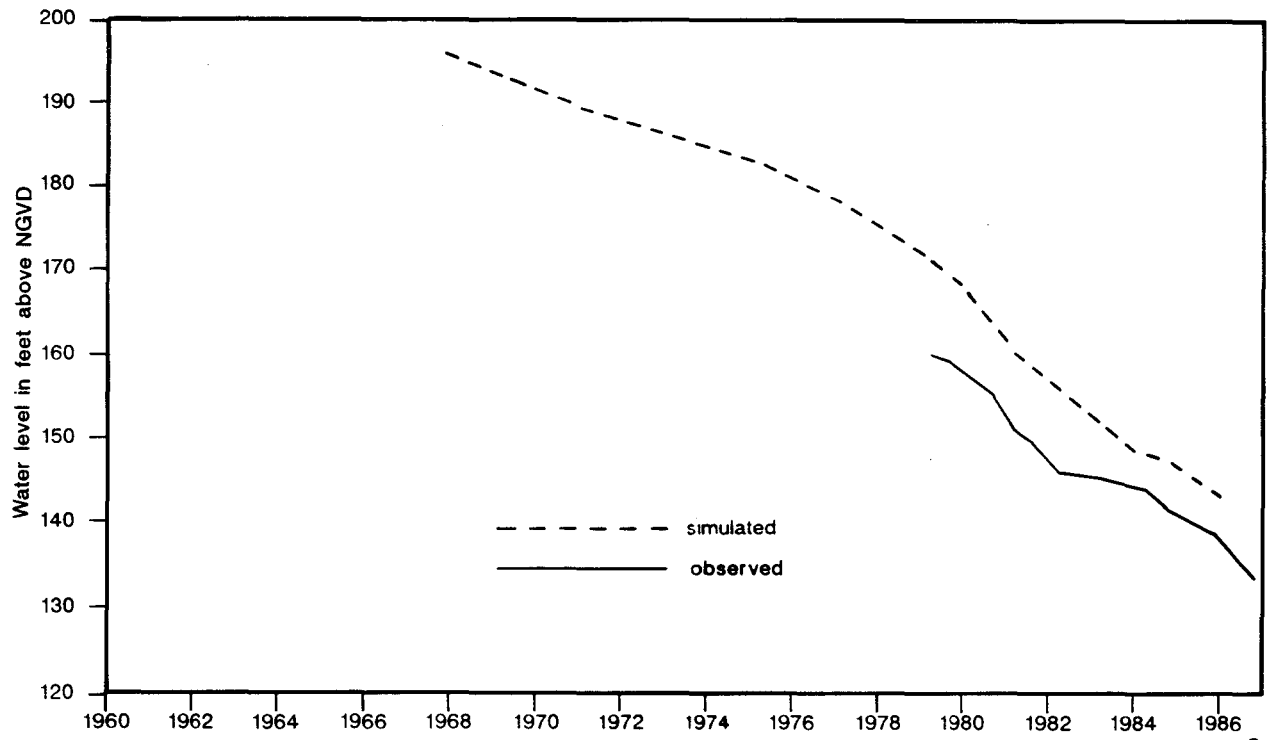
Figure II-33. (a) Simulated and observed heads at USGS test well 12, Clayton aquifer, Dougherty County and (b) simulated release of water from storage from 15 stress periods.
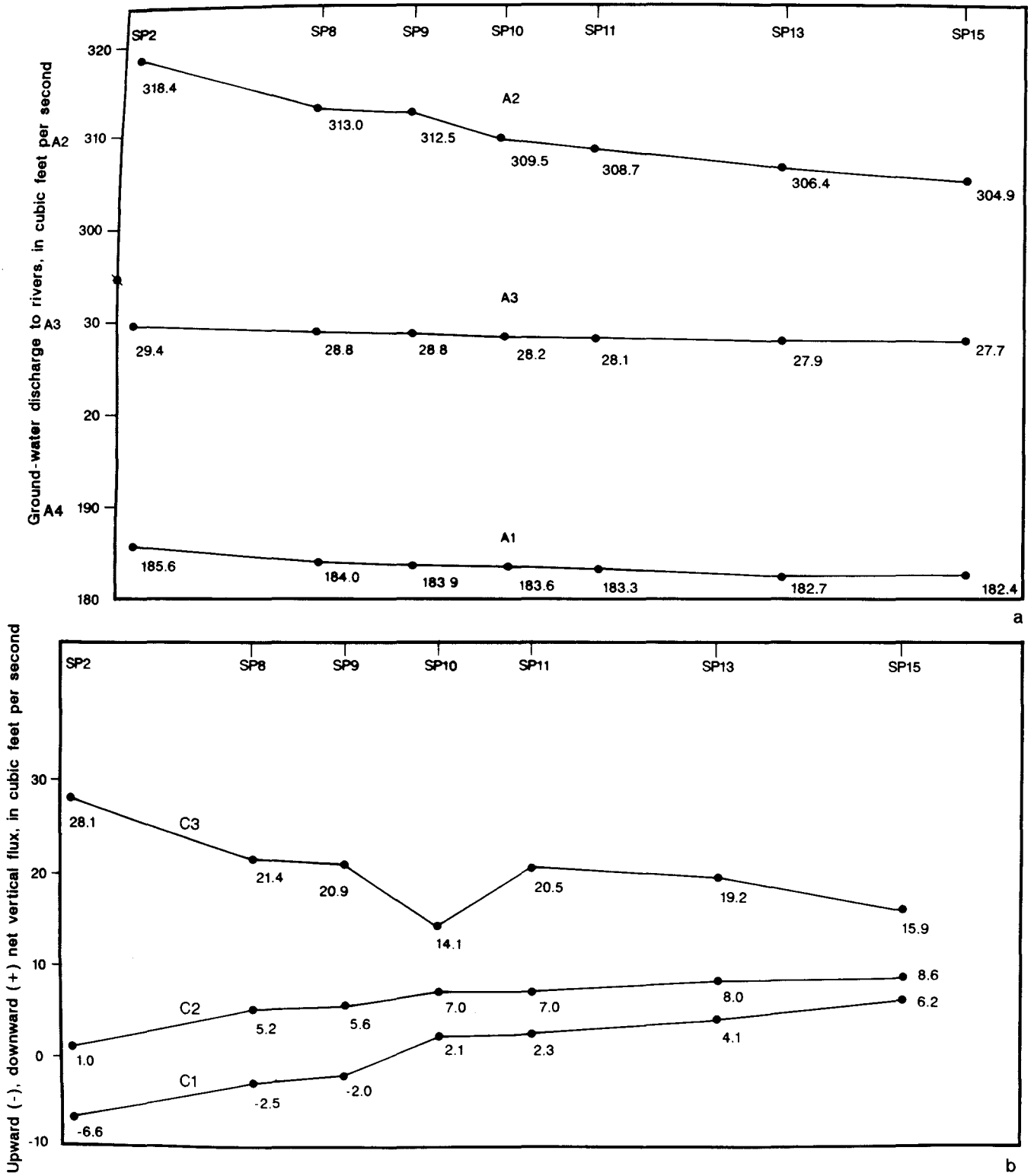
II-45

Figure II-34. (a) Simulated ground-water discharge to rivers for selected stress periods and (b) net vertical flux across each confining unit.
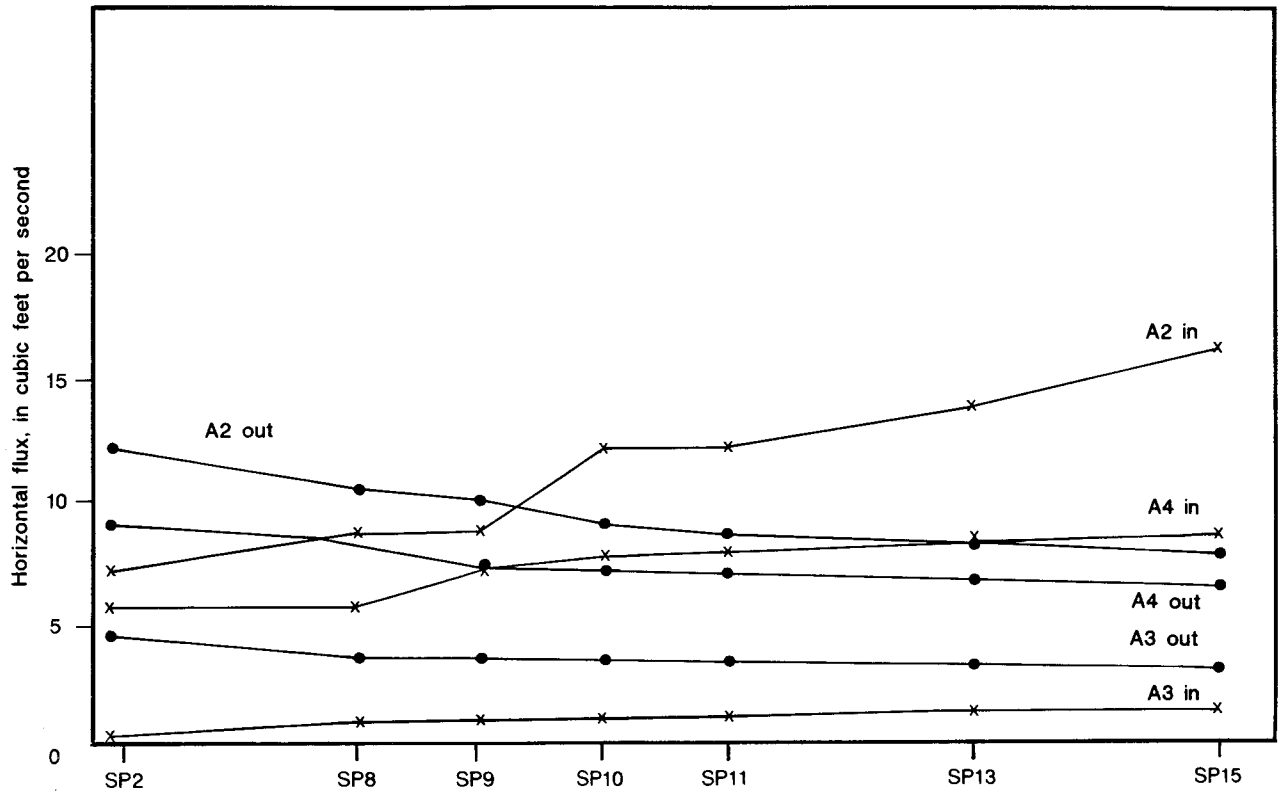
Figure II-35. Simulated horizontal fluxes in (x) and out (o) for each aquifer and selected stress periods.

Quantity: 250
Cost : $1,893.00