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AN IMPACT ANALYSIS OF THE GROUND WATER AND GEOLOGICAL EFFECTS OF POTENTIAL CONTROL OF THE SINKHOLE DISCHARGE AT HEAGY-BURRY PARK, ORANGE LAKE, FLORIDA

Final Technical Report

by

Louis H. Motz and Daniel P. Spangler
Faculty Investigators

Donard L. Strazimiri
Visiting Fulbright Investigator

and
Gaston Moffor
Graduate Student Investigator

Departments of Civil Engineering and Geology
University of Florida

for

Douglas A. Munch
Project Manager

St. Johns River Water Management District
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EXECUTIVE SUMMARY

Water levels in Orange Lake have fluctuated substantially during flooding and drought conditions over the period for which data are available. According to the U.S. Geological Survey (USGS), the highest lake level of 61.50 feet, referenced to the National Geodetic Vertical Datum of 1929 (ft, NGVD), occurred in November 1941, and the lowest level of 50.06 ft, NGVD, occurred in August 1956. In recent years, drought conditions and resulting low lake levels have occurred in the lake. It has been determined that vertical leakage from Orange Lake to the underlying ground water system is approximately 40 cubic feet per second (cfs), which makes up a relatively large part of the outflow component of the lake, particularly during drought periods when the lake level is low. Also, it has been determined that a substantial part of this vertical leakage occurs at a sinkhole complex in the southwestern part of Orange Lake adjacent to Heagy-Burry Park. Accordingly, consideration has been given to the idea of sinkhole intervention, i.e., stopping or at least reducing the discharge from Orange Lake at the sinkhole complex. As a result, the lake level would be maintained at a level higher than would occur naturally, thereby reducing the magnitude and duration of lake level declines during periods of drought.

The St. Johns River Water Management District (SJRWMD) has identified several water management alternatives that would maintain higher lake levels and/or reduce the duration of low water-level periods in Orange Lake during droughts. These sinkhole intervention measures, or sinkhole discharge control scenarios, would consist of plugging (or damming) the sinkhole complex, using a fixed crest weir to achieve passive control of the sinkhole complex discharge, or using a gated structure to achieve active control of the sinkhole complex discharge. Surface-water modeling already has been conducted by SJRWMD to evaluate the effects that the fixed crest weir and gated structure scenarios would have on lake levels and wetlands in the Orange Creek Basin, which includes Orange Lake. However, ground water modeling and geological investigations and interpretations are required to address more fully the impacts that would result from controlling the discharge from Orange Lake at the Heagy-Burry Park sinkhole complex. The additional interpretation includes an analysis of the effects that controlling the sinkhole discharge at Heagy-Burry Park would have on ground water levels and recharge and geologic stability of the surrounding karst landscape.

In December 1995, SJRWMD authorized the University of Florida (UF) to analyze the possible geologic and ground water effects of sinkhole discharge control in the Heagy-Burry Park area. Based almost entirely on existing data, a ground water model was developed to evaluate local ground water levels and drawdowns in the area that is affected by the sinkhole discharge. Also, possible different effects for drought and high rainfall periods for the sinkhole discharge control scenarios were investigated. From the ground water model results, the geologic stability of the karst landscape for both the lake and surrounding land area, where numerous sinkhole and subsidence areas already exist, was evaluated relative to the sinkhole discharge control scenarios.

The study area covers approximately 203 square miles in north-central Florida centered on the Heagy-Burry Park sinkhole complex in Orange Lake, and it includes parts of southeastern Alachua and north-central Marion counties. Orange and Lochloosa lakes are shallow, flat-bottomed lakes that are the principal surface-water bodies in the study area. Along with Newnans Lake and Orange Creek, they make up the Orange Creek Basin. The Lochloosa Lake subbasin occupies an area of nearly 86 square miles (mi^2), and the lake itself has a surface area of approximately 5,600 acres, a mean depth of about 7 ft, and a maximum depth of 11 ft. The principal surface-water outflow from Lake Lochloosa is through Cross Creek to Orange Lake. Orange Lake is larger than Lochloosa Lake, with a subbasin of 127 mi^2. Cross Creek on the northeast side of Orange Lake and River Styx on the northwest side of the lake are the two principal surface-water inflows to the lake, and Orange Creek on the east side of the lake is the principal surface-water outflow. The depth of Orange Lake ranges mostly from 7 to 12 ft at the normal lake level of 58 ft, NGVD.

The ground water system in the study area generally consists of a surficial aquifer system that overlies a low permeability confining unit, which in turn overlies the Floridan aquifer system, a regionally extensive aquifer system. The surficial aquifer system consists of Pliocene, Pleistocene, and Recent deposits, and it is under water-table conditions. The confining unit is called the upper confining unit for the Floridan aquifer system, and it is comprised of sediments of the Miocene age Hawthorn Group, and, locally, deposits of Pliocene age. The Floridan aquifer system in the study area is made up of carbonate formations that consist of the Ocala Limestone of late Eocene age, the Avon Park Formation of middle Eocene age, the Oldsmar Formation of early Eocene age, and the Cedar Keys Formation of Paleocene age. In the eastern part of the study area, the Floridan aquifer system is comprised of two zones called the Upper and Lower Floridan aquifers, which are separated by a relatively low permeability unit called the middle semiconfining unit. The Upper Floridan aquifer is a zone of high permeability contained within the Ocala Limestone and the upper third of the Avon Park Formation. The Lower Floridan aquifer is contained within the lower part of the Avon Park Formation, the Oldsmar Formation, and the upper third of the Cedar Keys Formation.

The Upper Floridan aquifer is mostly unconfined in the western and southwestern parts of the study area, and it is confined in the eastern and northeastern parts of the area. During the evaluation period (1985-1995), ground water levels in the Upper Floridan aquifer ranged from highs in September 1988 of about 50 ft, NGVD, in the south and 65 ft, NGVD, in the northeast to lows in May 1991 of about 43 ft, NGVD, in the south and 60 ft, NGVD, in the northeast. Ground water levels fluctuated from highs in September 1988 to lows in May 1991 as much as 8 ft in the south-central part of the study area. Based on potentiometric maps of the Upper Floridan aquifer, ground water flow in the aquifer is from the northeast to the west and south. The boundary between the unconfined and confined regions can be delineated by a demarcation line on the potentiometric surface that shifts westward as ground water levels increase seasonally and eastward as ground water levels decrease seasonally.

The USGS modular three-dimensional finite-difference ground water code MODFLOW was used to model the ground water system in the study area. The basic (BAS), block-centered flow, version 2 (BCF2), well (WEL), river (RIV), evapotranspiration (ET), general head boundary (GHB), recharge (RCH), strongly implicit procedure (SIP), and output control option (OC) packages were used. A ground water model was developed and calibrated by simulating the May 1991 (low water level) potentiometric surface, and then the model was verified by simulating the September 1988 (high water level) potentiometric surface. The hydrogeologic system was considered to consist of three layers, or aquifer units, separated by confining units. Layer one represents the surficial aquifer and the Hawthorn Group, which is the upper confining unit for the Floridan aquifer system. Layer two represents the Upper Floridan aquifer, which is confined in the northeastern and eastern parts of the area and unconfined everywhere else. The intersection of the water table in the Upper Floridan aquifer in layer two with the bottom of the Hawthorn Group in layer one separates the confined and unconfined parts of the Upper Floridan aquifer. The confining unit between layers two and three represents the middle semiconfining unit in the eastern part of the study area, and layer three represents the Lower Floridan aquifer. The RIV and BCF2 packages in MODFLOW were used to represent the discharge from Orange and Lochloosa lakes to the Upper Floridan aquifer.

The study area was discretized into 35 rows and 35 columns that range in size from 100 to 5,000 feet. To model the sinkhole complex in Orange Lake, the main sinkhole at Heagy-Burry Park was simulated in the center of the grid with dimensions 100 ft by 100 ft. Two adjacent cells, one to the west and the other to the south, with dimensions 100 ft by 150 ft were used to simulate the other sinkholes that are adjacent to the main sinkhole. Constant head cells were assigned to layer one in the northeastern part of the area between Orange and Lochloosa lakes and the boundaries of the model. Cells in layer one were active in the model area west and south of Orange Lake where the Upper Floridan aquifer is confined. Cells in layer one were inactive in the area farther west and southwest where the Upper Floridan aquifer is unconfined. In layers two and three, the boundary cells were general head boundaries, and all of the other cells in these layers were active cells.

The May 1991 simulation was run to steady state, with one stress period and one time step equal to 1.0 day. During the calibration, values for transmissivity in layer two (T_2), vertical leakage in layer one (V_{contl}), conductances of the lake bed sediments in the RIV package, and the conductances for the general head boundaries in layer two were adjusted until the calculated and observed heads in layer two for May 1991 were within reasonable agreement. In this simulation, the value for hydraulic conductivity in layer one is $K_1 = 5.0 \times 10^{-3}$ ft/day, and the bottom elevation of layer one is an array based on logs from 25 wells in the study area. The values of vertical leakance for layer one (V_{cont1}) range from 1.5×10^{-3} to 4.5×10^{-3} day^{-1} in the area just east of the demarcation line, where the Upper Floridan aquifer is semiconfined, and up to 7.5×10^{-4} day^{-1} in the northeast area of the model, where the Upper Floridan aquifer is confined. The top elevation for layer two is an array that is equal to the bottom elevation of layer one. Values for transmissivity in layer two range from 100,000 ft^2/day in the northeastern part of the model, where the Upper Floridan aquifer is confined, to 6,000,000 ft^2/day in the south-central part of the model area, where the Upper Floridan aquifer is unconfined and receives maximum recharge. Vertical leakance for layer two (V_{cont2}) was assigned a value of 1.0×10^{-5} day^{-1} in the eastern part of the study area, where the middle semiconfining unit is present, and a value of 1.0×10^{-2} day^{-1} in the western part of the study area, where the middle semiconfining unit is absent. The transmissivity for layer three was set equal to 200,000 ft^2/day.

In the May 1991 simulation, the lake stages were 53.97 ft, NGVD, for Orange Lake and 55.44 ft, NGVD, for Lochloosa Lake in the RIV package. The values of conductance for the three cells in the RIV package that represent the lake bed sediments at the sinkholes in Orange Lake range from 400,000 to 800,000 ft^2/day, and the vertical leakance (V_{cont1}) for these cells in the BCF2 package that represent the confining unit between layers one and two at the sinkholes ranges from 12 to 30 day^{-1}. Recharge was applied to layer one where the cells are active and to layer two in the area where layer two is unconfined and the cells in layer one are inactive. The rainfall for May 1991 was 0.333 ft, and it was applied as net recharge based on ratios developed to represent the percent of rainfall that was net recharge. These ratios, based on soil maps and published literature, are 4 percent for the northwestern part of the model area, 29 percent for the southwestern and central parts of the area, and 40 percent for the area in the south where a large number of sinkholes are present. In the May 1991 simulation, evapotranspiration generally occurs from only the active cells in layer one that are not covered by Orange and Lochloosa lakes, and the maximum evapotranspiration rate from these cells is 37.0 inches/year. Pumping in the study area is represented by 21 wells in layer two.

For the May 1991 simulation that was considered calibrated, the mean of the differences between calculated and observed heads is 0.066 ft, and the standard deviation of the differences is 0.448 ft. The net discharge, which is the sum of the discharge from Orange and Lochloosa lakes to the Upper Floridan aquifer minus a relatively small component of flow from the ground water system into the lakes, is 3.43×10^6 ft^3/day for this simulation, and about 90 percent of this (36 cfs) discharges at the sinkhole complex in Orange Lake.

The model calibrated for the May 1991 potentiometric surface was verified by running it for September 1988 conditions. In the verification step, the heads at the general head boundaries were changed based on the observed potentiometric map for September 1988. Rainfall for September 1988 was 0.917 ft, and it was applied as net recharge using the same net recharge-rainfall ratios used in the May 1991 simulation. The lake stages were 57.72 ft, NGVD, for Orange Lake and 58.16 ft, NGVD, for Lochloosa Lake, and the pumping rates for the wells in layer two were adjusted for September water use. Otherwise, the hydrologic parameters in the model were the same. For the September 1988 verification, the mean of the differences between the calculated and observed heads is -0.36 ft, and the standard deviation of the differences is 0.44 ft. The net discharge from Orange and Lochloosa lakes to the Upper Floridan aquifer is 2.29×10^6 ft^3/day.

A 23-month period from November 1, 1989, to September 30, 1991, was selected for a transient simulation, which was divided into 23 stress periods (equal to the number of months) because the net recharge, pumping rates, lake stages, and boundary heads all changed each month. The MODFLOW input files for the May 1991 simulation were modified to include the parameters that changed during the transient simulation. The net recharge was changed based on monthly rainfall data from November 1989 to September 1991. The pumping rates for the wells in layer two were changed based on seasonal water use considerations. The stages at Orange and Lochloosa lakes were changed based on monthly simulations for this period by SJRWMD. The heads at the general head boundaries were changed for every month based on interpolation between May and September potentiometric maps. Also, the storage coefficients were modified for the transient simulation. The active cells in layer one were assigned an unconfined aquifer storage coefficient of 0.1. Layer two was assigned a primary (confined) storage coefficient of 0.001 and a secondary (unconfined) storage coefficient of 0.3. Layer three was assigned a confined aquifer storage coefficient of 0.001. The heads calculated for layer two during the transient simulation matched observed ground water levels reasonably well, but the data available for comparison are very limited. The net discharge from Orange and Lochloosa lakes to the Upper Floridan aquifer for the transient simulation is 3.28×10^6 ft^3/day.

The impacts of controlling the sinkhole-complex discharge were evaluated by modeling the changes in ground water levels in the Upper Floridan aquifer that would result from the three hypothetical sinkhole complex discharge control scenarios. The first scenario consists of completely stopping the sinkhole discharge during both low and high water-level periods (scenarios 1.a. and 1.b., respectively) by plugging the sinkhole or constructing a dam around the sinkhole complex. The second scenario consists of using a fixed crest weir to achieve passive control of the sinkhole discharge when the level of Orange Lake drops below 56, 55, or 54 ft, NGVD (scenarios 2.a., 2.b., and 2.c., respectively). The third scenario consists of operating a gated structure to achieve active control of the sinkhole discharge when the lake level drops below 56, 55, or 54 ft, NGVD (scenarios 3.a., 3.b., and 3.c., respectively); the gate would be re-opened when the lake level rises above 58 ft, NGVD. For scenario one, impacts relative to drought conditions were evaluated relative to the May 1991 potentiometric surface, and impacts relative to a high rainfall period were evaluated relative to the September 1988 potentiometric surface. For scenarios two and three, transient simulations were performed and compared to the simulation of existing conditions in the period from November 1989 to September 1991.

Reducing the sinkhole discharge by plugging (or damming) the sinkhole complex or by installing a weir or gate will reduce the net discharge from Orange and Lochloosa lakes to the Upper Floridan aquifer and reduce ground water levels in the Upper Floridan aquifer. For scenario one, during the simulated May 1991 dry period (scenario 1.a)., the decrease in the ground water level in the Upper Floridan aquifer will be 1.54 ft at the sinkhole complex, and the net discharge from Orange and Lochloosa lakes will be reduced from 3.43×10^6 to 3.45×10^5 ft^3/day, or about 89.9 percent. During the simulated September 1988 wet period (scenario 1.b.), the decrease in the ground water level in the Upper Floridan aquifer will be 1.03 ft at the sinkhole complex, and the net discharge from Orange and Lochloosa lakes will be reduced from 2.29×10^6 to 2.25×10^5 ft^3/day, or about 90.2 percent.

In scenario two, the greatest impact on ground water levels will be due to scenario 2.a., in which the weir is set at 56 ft, NGVD. In this scenario, the decrease in the ground water level in the Upper Floridan aquifer at the sinkhole complex will be slightly greater than 1 foot, and the net discharge from Orange and Lochloosa lakes will be reduced from 3.28 × 10^6 ft^3/day to 2.78 × 10^6 ft^3/day, or about 15.2 percent. For scenarios 2.b. and 2.c., in which the weir is set at 55 and 54 ft, NGVD, respectively, the impacts will be less. The duration of the ground water level changes will be shorter, and the reductions in net discharge from the lakes will be about 11.3 and 1.2 percent, respectively.

In scenario three, the greatest impact on ground water levels will be due to scenario 3.a., in which the gate will be closed when the lake level drops to 56 ft, NGVD. In this scenario, the decrease in the ground water level in the Upper Floridan aquifer at the sinkhole complex will be about 1 foot. The net discharge from Orange and Lochloosa lakes will be reduced from 3.28 × 10^6 to 1.42 × 10^6 ft^3/day, or about 56.7 percent. For scenarios 3.b. and 3.c., in which the gate will be closed when the lake level drops to 55 and 54 ft, NGVD, respectively, the impacts on ground water levels will be less. The duration of the ground water level changes will be shorter, and the reductions in net discharge from the lakes will be about 42.1 and 29.6 percent, respectively.

In all of the scenarios, the greatest impact that controlling the sinkhole-discharge complex will have on ground water levels in the Upper Floridan aquifer will be at the sinkhole complex, where the maximum decrease will be on the order of 1.5 ft. The impact will diminish spatially and be negligible within a few miles from Orange Lake. The maximum changes in ground water levels that would be associated with controlling the sinkhole-discharge complex are on the order of 20 percent of the changes that already occur between naturally occurring wet and dry periods.

The impact that controlling the sinkhole-discharge complex will have on geologic stability was evaluated in terms of geologic and hydrologic criteria. These criteria were based on the hydrogeologic profiles developed during the investigation, changes in lake levels, spatial impacts of the scenarios, the magnitude of ground water level fluctuations in the Upper Floridan aquifer, existing sinkhole and karst features in the study area, the extent of unconfined conditions in the Upper Floridan aquifer, and characteristics of the overlying confining unit where it is present.

Scenario two most likely will have the greatest impact on geologic stability. Lake-level increases above existing conditions will be greatest for scenario 2.a. Relatively rapid transient changes are predicted to occur in ground water levels in the Upper Floridan aquifer at the sinkhole complex for this scenario, which thus will have the greatest impact on geologic stability. The impacts will be less for scenarios 2.b. and 2.c., in which the transient changes in ground water levels also will occur but less frequently than in scenario 2.a. Scenario three likely will have an intermediate impact on geologic stability. Lake-level increases above existing conditions will be greatest for scenario 3.a., and also the duration of ground water level decreases will be greatest for this scenario. Ground water level decreases also are predicted for scenarios 3.b. and 3.c., but the duration of these changes will be less, and thus the impact on geologic stability also will be less. Scenario one likely will have the least impact on geologic stability. The maximum predicted decrease in the ground water level in the Upper Floridan aquifer is greater than in the other scenarios, but this scenario does not involve superimposing additional transient changes on ground water levels in the Upper Floridan aquifer.

In this project, the geologic and hydrologic aspects of controlling the discharge at the Heagy-Burry Park sinkhole complex were investigated. The maximum reduction in ground water levels in the Upper Floridan aquifer due to sinkhole discharge control is on the order of 20 percent of the maximum natural changes that occurred in ground water levels in the Upper Floridan aquifer between highs and lows that occurred in September 1988 and May 1991 during the 1985-1995 period of evaluation. Significant reductions in the net discharge from Orange and Lochloosa lakes (about 90 percent of which occurs at the sinkhole-discharge complex) to the Upper Floridan aquifer will occur, particularly in scenarios 1.a., 1.b., 3.a., and 3.b, and to a lesser extent in the other scenarios. Intense transient changes, particularly the rapid and repeated transient changes associated with scenario 2.a., should be avoided, i.e., there should be no rapid artificial control of Orange Lake, the ground water levels in the Upper Floridan aquifer, or the discharge from Orange Lake to the Upper Floridan aquifer. It is important to recognize that investigating the structural aspects of the proposed scenarios was not in the scope of this investigation and thus was not addressed. At this point, if one or more of the scenarios is to be considered further, detailed geotechnical studies and hydrogeologic characterization of the sinkhole complex need to be performed to determine the characteristics of the bottom of Orange Lake in the vicinity of the sinkhole complex. Also, additional hydrologic studies should be performed to investigate the impacts that extreme drought and wet periods (such as occurred in 1956 and 1941, respectively) would have on the proposed scenarios.

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ABSTRACT

In recent years, drought conditions and resulting low lake levels have occurred in Orange Lake. A substantial part of the vertical leakage from Orange Lake to the underlying ground water system occurs at a sinkhole complex in the southwestern part of Orange Lake adjacent to Heagy-Burry Park. Consideration has been given to stopping or at least reducing the discharge from Orange Lake at the sinkhole complex in order to maintain the lake at a level higher than otherwise would occur, thereby reducing the magnitude and duration of lake level declines during a drought. Surface-water modeling already has been conducted to evaluate the effects that proposed control measures would have on lake levels and wetlands in the Orange Creek Basin, which includes Orange Lake. However, ground water modeling and geological investigations are required to address more fully the impacts that would result from controlling the sinkhole-complex discharge. Accordingly, the USGS ground water code MODFLOW was used to evaluate the hydrogeologic impacts of three sinkhole discharge control scenarios, which would consist of plugging (or damming) the sinkhole complex, using a fixed crest weir to achieve passive control of the sinkhole discharge, and using a gated structure to achieve active control of the sinkhole discharge. Based on these results, depending on the scenario chosen, the discharge from Orange and Lochloosa lakes to the Upper Floridan aquifer will be reduced by as much as 90 percent and ground water levels in the Upper Floridan aquifer will be reduced by a maximum of about 1.5 ft at the sinkhole complex. The fixed crest weir scenario will have the greatest impact on geologic stability due to relatively rapid and repeated transient changes that will occur in ground water levels in the Upper Floridan aquifer at the sinkhole complex.

1.0 INTRODUCTION

1.1 BACKGROUND

Water levels in Orange Lake have fluctuated substantially during flooding and drought conditions over the period for which data are available. According to the U.S. Geological Survey (USGS), the highest lake level of 61.50 feet, referenced to the National Geodetic Vertical Datum of 1929 (ft, NGVD), occurred in November 1941, and the lowest level of 50.06 ft, NGVD, occurred in August 1956. In recent years, drought conditions and resulting low lake levels have occurred in the lake. It has been determined that vertical leakage from Orange Lake to the underlying ground water system is approximately 40 cubic feet per second (cfs), which makes up a relatively large part of the outflow component of the lake, particularly during drought periods when the lake level is low. Also, it has been determined that a substantial part of this vertical leakage occurs at a sinkhole complex in the southwestern part of Orange Lake adjacent to Heagy-Burry Park. Accordingly, consideration has been given to the idea of sinkhole intervention, i.e., stopping or at least reducing the discharge from Orange Lake at the sinkhole complex. As a result, the lake level would be maintained at a level higher than would occur naturally, thereby reducing the magnitude and duration of lake level declines during periods of drought.

The St. Johns River Water Management District (SJRWMD) has identified several water management alternatives that would maintain higher lake levels and/or reduce the duration of low water-level periods in Orange Lake during droughts. These sinkhole intervention measures, or sinkhole discharge control scenarios, would consist of plugging (or damming) the sinkhole complex, using a fixed crest weir to achieve passive control of the sinkhole complex discharge, or using a gated structure to achieve active control of the sinkhole complex discharge. Surface-water modeling already has been conducted by SJRWMD to evaluate the effects that the fixed crest weir and gated structure scenarios would have on lake levels and wetlands in the Orange Creek Basin, which includes Orange Lake. However, ground water modeling and geological investigations and interpretations are required to address more fully the impacts that would result from controlling the discharge from Orange Lake at the Heagy-Burry Park sinkhole complex. The additional interpretation includes an impact analysis of the effects that controlling the sinkhole discharge at Heagy-Burry Park would have on ground water levels and recharge and geologic stability of the surrounding karst landscape.

1.2 OBJECTIVES

In December 1995, SJRWMD authorized the University of Florida (UF) to analyze the possible geologic and ground water effects of sinkhole discharge control in the Heagy-Burry Park area. Based on existing data, a ground water model was developed to evaluate local ground water levels and drawdowns in the area that is affected by the sinkhole discharge. Also, possible different effects for drought and high rainfall periods and various sinkhole discharge control scenarios were investigated. Using interpretations from the ground water model results, the geologic stability of the karst landscape for both the lake and surrounding land areas, where numerous sinkhole and subsidence areas already exist, was evaluated relative to the sinkhole discharge control scenarios.

1.3 TASKS

To meet the objectives of the ground water modeling and the geologic investigations, the project was divided into five tasks. Hydrogeologic characterization and compilation of existing data (Task One) were accomplished, and the information thus collected was used to construct a ground water model (Task Two). An impact analysis (Task Three) was performed based on the ground water model results, and a draft report was prepared (Task Four). After review of the draft report, this final report (Task Five) was prepared for SJRWMD.

In Task One, existing hydrologic and hydrogeologic data were compiled for the Heagy-Burry Park area at Orange Lake. The various types of data that were compiled included well logs, water-level measurements, potentiometric maps, water-table maps, geophysical logs, hydrogeologic cross-sections, pump test data, water-use data for wells in the area, well location maps, bathymetric surveys, soil maps, land use maps, chronological aerial photography, and historical characterization. The methodology for collecting these data included conducting field work, relying on previous and current work by SJRWMD and the U.S. Geological Survey (USGS), and also relying on relevant information at UF.

In Task Two, using the data compiled in Task One, a conceptual model of the hydrology of the Heagy-Burry Park area was developed. Based on the conceptual model, the numerical ground water code MODFLOW (McDonald and Harbaugh 1988) was selected and a model was calibrated to existing conditions. Surface-water levels in Orange and Lochloosa lakes were included in the model as input data, and the model was run for drought and high rainfall periods to evaluate different possible effects. Control of the sinkhole discharge was taken into consideration by determining the changes in ground water levels that will result from three hypothetical sinkhole discharge control scenarios.

In Task Three, an impact analysis was conducted based on the data compiled in Task One and the ground water model calibrated as part of Task Two. This analysis included the possible effects of sinkhole discharge control on ground water recharge and geologic stability of the surrounding karst landscape for drought and high rainfall periods and for the sinkhole discharge scenarios performed in Task Two. The geologic stability of the surrounding karst area was evaluated in a relative sense, based on selected criteria developed from geologic and geomorphic profiles, changes in lake levels, areal impact, water-level fluctuations, and the proximity of other sinkholes and karst features. Further criteria were based on determining areas where the top of the Upper Floridan aquifer would be dewatered, thus developing additional void spaces where sinkholes would likely occur more frequently.

Task Four consisted of the preparation of a draft technical report, including an evaluation of the geologic and hydrologic data assembled in Task One, a description of the conceptual model developed for Task Two, calibration of parameters, sensitivity analysis, model verification, and simulation of existing conditions accomplished in Task Two, and the impacts of the sinkhole discharge control scenarios accomplished in Task Three. Task Five consisted of preparing this final technical report after the draft technical report had been reviewed by SJRWMD.

2.0 GEOLOGY

2.1 LOCATION

The study area covers approximately 203 square miles in north-central Florida (see Figure 2-1). It is centered on the Heagy-Burry Park sinkhole complex in Orange Lake, and it lies between 29° 18' 30" and 29° 37' 30" north latitude and 82° 05' 30" and 82° 20' 00" west longitude. Parts of southeastern Alachua and north-central Marion counties are in the study area.

2.2 GEOLOGIC FEATURES

Geophysical logs for some wells in the project area obtained from SJRWMD depict geologic, stratigraphic, lithologic, and hydrostratigraphic units to be basically similar to those of regional north-central peninsular Florida. However, these units are not continuous throughout this area, and their thicknesses vary considerably. The Fairfield Hills, which are considered by White (1970) to be remnants of a former upland surface, constitute the highest points within the project area at approximately 75 to 210 feet, National Geodetic Vertical Datum of 1929 (ft, NGVD)(formerly called mean sea level) and contain the units indicated in Table 2-1. The Orange Lake plain, with its shallow, flat-bottomed lakes, lies east of the topographic high feature of the Fairfield Hills. The mean elevation of Orange Lake at the Heagy-Burry Park gaging station is about 58 ft, NGVD. Because of the difference in elevation between the Fairfield Hills and the Orange Lake plains, an escarpment has resulted. This escarpment most probably has shifted

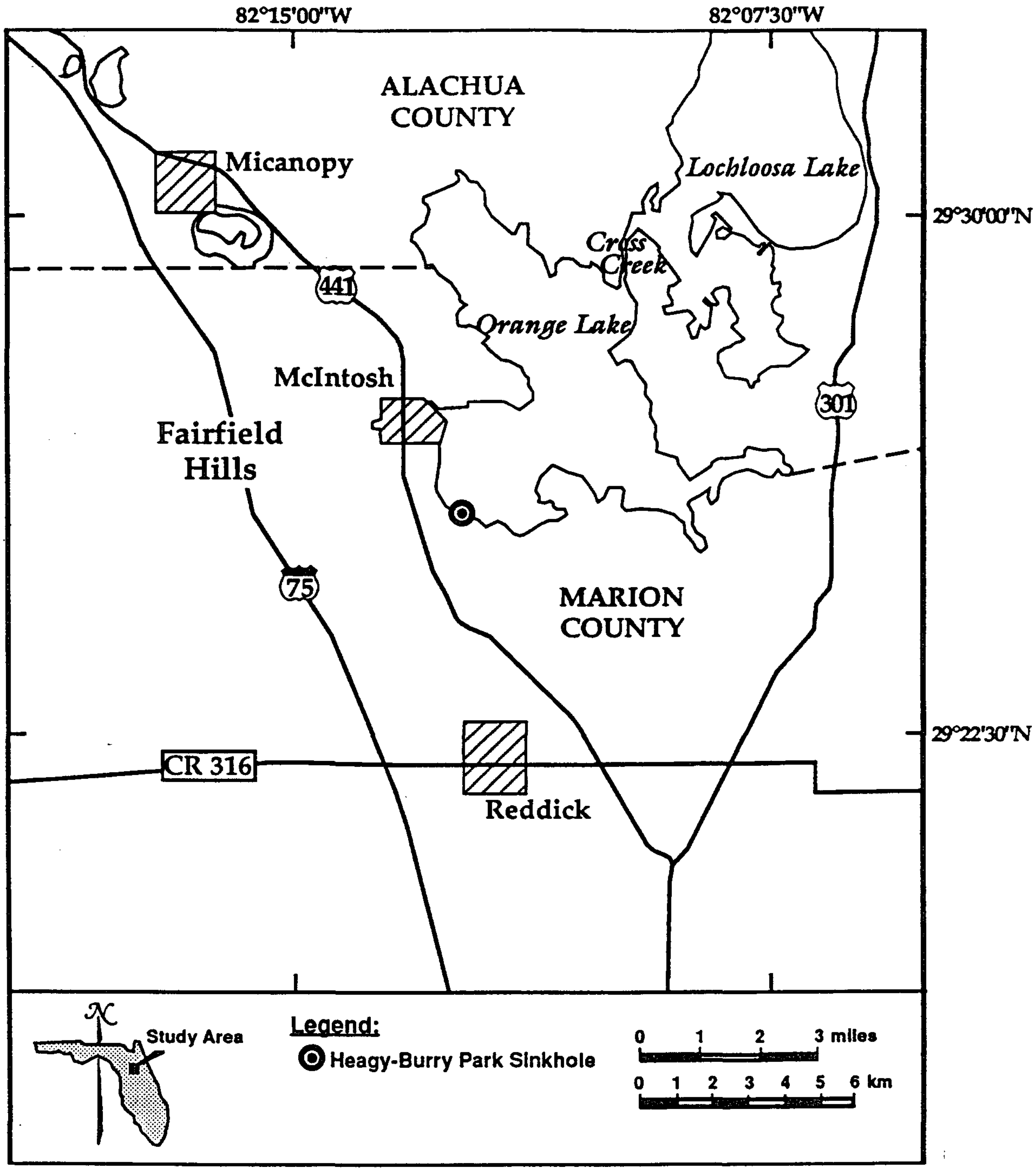


Figure 2-1. Study Area

Table 2-1. Shallow generalized geologic column in the Heagy-Burry Park Orange Lake area

Geologic Series	Time Before Present (10^6 years)	Formation or Group	Approximate Thickness (feet)	Lithologic Description
Pleistocene and Recent	1.6 - 0.01	Undifferentiated Younger Marine and Estuarine Terrace Deposits (Post-Hawthorn Deposits - Sands and Clays)	0 -10	Discontinuous fine to coarse grained, loose sand, clayey- sand, sandy clay, marl, shell, and clay.
Pliocene	5.3 - 1.6	Undifferentiated Younger Marine and Estuarine Terrace Deposits (Post-Hawthorn Deposits - Sands and Clays)	0 -10	Interbedded clay and clayey sand, fine to medium grained, well sorted sand, shell, and soft limestone.
Miocene	24 - 5.3	Hawthorn Group	0 - 120	Highly variable, interbedded greenish clay, clayey-sand, quartz sand, sandy-clay, shell, carbonates and phosphate.
Oligocene	37 - 24	Absent	Absent	Absent
Eocene	57 - 37	Ocala Limestone	Approximately 4,100	Tan to cream, soft fossiliferous limestone, grainstone to wackestone
		Avon Park Formation		Tan to brown dolostone and limestone

Sources: Adapted from Barmiest et al. 1963, Clark et al. 1964, Fairchild 1972, Lane and Hoenstine 1991, Leve 1966, Miller 1986, Scott 1988 westward through geological time, due to trenching, weathering, erosion, dissolution, collapse, subsidence, and infilling from the topographically higher Fairfield Hills.

The structurally high feature of the Ocala Platform, formerly called the Ocala Uplift, influences the geology of this area considerably. This is evidenced by strata dipping to the northeast. As a result, the Ocala Limestone of the Floridan aquifer system, which is mostly exposed or occurs at relatively shallow depths in the west and southwest, is covered by a progressively thickening sequence of Hawthorn Group sediments and occurs at a much greater depth in the east and northeast (Hoenstine and Lane 1991). Furthermore, a veneer of Post-Hawthorn Group deposits unconformably covers the area in various places.

2.3 PRE-HAWTHORN GROUP DEPOSITS

2.3.1 Eocene Series

The Ocala Group Limestones of the Late Eocene epoch (approximately 38 to 40 million years ago, mya) are the oldest exposed rocks in the project area. These rocks were deposited in a shallow marine environment just like the Avon Park Formation of the Middle Eocene Epoch (approximately 47-43 mya), which they overlie. Test drilling for oil has yielded an underlying thick sequence of carbonate sedimentary rocks (limestone and dolomite), which are mantled by siliciclastic sediments composed of quartz sand, silt, clayey sand, and sand. Metamorphic basement rocks are encountered at a depth of approximately 4,200 feet below land surface (Lane and Hoenstine 1991).

Limestones of the Ocala Group have been subdivided and renamed several times. In 1884, the exposed Florida limestone was correlated with the Vicksburg Limestone of Mississippi and Alabama by E. A. Smith. Dall and Harris (1892) first used the term Ocala Limestone to describe the rock that was quarried and exposed near Ocala in Marion County. Formerly, the Ocala Group was subdivided from oldest to youngest into the Inglis, Williston, and Crystal River Formations (Puri 1957). Miller (1986) divides the Ocala Limestone into two parts, an upper and lower unit. The lower unit is said to consist of fine-grained limestone of variable hardness that contains an abundance of marine fossils. This lower unit may also contain variable amounts of dolomite in places. Meanwhile, the upper unit is described as a soft, porous coquina, composed of shells and other marine fossils that are loosely bound into a limestone matrix. Such distinct subdivisions of the Ocala Group are not made in this report.

The top surface of the Ocala Limestone is irregular. This is due to the dissolution of carbonate rocks when they come in contact with ground water. As a result, cavities, underground conduits, and caves have been observed within carbonate units (Schultz and Cleaver 1955). The dissolution of the Ocala Group Limestone has greatly enhanced the primary porosity of the unit, making it one of the most prolific rock units in the Floridan aquifer system (Miller 1986). Abandoned limestone quarries and caves within the project area provide excellent observation sites for typical Ocala Group Limestone samples. Here, the Ocala Group Limestone commonly occurs as a soft, white to cream, fossiliferous limestone, characteristic of the upper part of the formation. Other Ocala Limestone rocks range from poorly to moderately indurated, moderately to highly porous and permeable, relatively pure limestone ($CaCO_3$) to a less porous, highly indurated dolomite ($CaMg(CO_3)_2$). Chert boulders and/or irregular flint masses were observed in abundance near the top of the Ocala Group throughout the project area. Some chert / flint rocks were observed by the authors of this report along cracks and fissures at the caves within the quarries south of Orange Lake.

Marine fossils associated with the Ocala Limestone include foraminifera, mollusks, bryozoans, and echnoids indicating that deposition took place in a shallow marine setting. The distinctive foraminifera genus *Lepidocyclina*, which is used as a guide for identifying the Ocala Group Limestone, is common to abundant. Thickness of the unit is quite variable, ranging from less than 50 feet to approximately 190 feet (Lane and Hoenstine 1991). Variations in thickness may be due to limestone removal by dissolution and/or erosion of insoluble matter in the process of karst landscape formation.

2.3.2 Oligocene Series

The Oligocene epoch (from approximately 37 mya to 24 mya) is only sparingly represented in north-central Florida as the Suwannee Limestone. However, in the Orange Lake subbasin area, such a formation has not been reported. This unit may have been removed by the erosion of insoluble deposits or the dissolution of limestone. Moreover, the unconformity on top of the Ocala Group represents an interval of erosion and/or dissolution or nondeposition that includes the uppermost Eocene, the entire Oligocene, and in some areas, the basal Miocene (Scott 1983).

2.4 THE HAWTHORN GROUP

2.4.1 Miocene Series

Because of the absence of Oligocene deposits in the entire project area, the Ocala Group is overlain by the younger Miocene Series Hawthorn Group. These sediments were unconformably deposited in a shallow marine environment approximately between 25 to 6 mya, have surface or near-surface occurrences throughout the project area, and consist of widely varying mixtures of interbedded phosphatic clay, quartz sand, dolomite and limestone (Scott 1983 and 1988). Because this formation contains a mixture of various rock types, Scott (1988) noted it as a "junk" formation. In 1880, the phosphatic beds in Alachua and Columbia counties were referred to as the Waldo Formation by L. C. Johnson. These phosphate layers were later described in 1892 as Hawthorn beds by Dall and Harris. Pirkle (1957) writes of the Hawthorn Formation (Middle Miocene) as being characteristically quite heterogeneous. He states that it is composed largely of various combinations of quartz sand, clay, carbonate (both calcic and dolomitic), and phosphate pebbles and grains. Although these materials often change laterally and vertically over short distances, and lenses of nearly pure clay or sand occur occasionally, phosphate grains found throughout the formation are characteristic of the unit. Puri and Vernon (1964) suggest that the Hawthorn may be the most misunderstood formational unit in the southeastern United States. They state further that it has been the dumping ground for alluvial, terrestrial, marine, deltaic, and prodeltaic beds of diverse lithologic units in Florida and Georgia that are stratigraphic equivalents of the Alum Bluff Stage.

Sand is a major constituent of the Hawthorn Formation, occurring as medium to fine in size. Clays are present throughout much of the formation either as accessory minerals or as clay beds. The authors of this report observed brownish to greenish, sandy, sometimes clayey, phosphatic carbonates within Hawthorn formation samples taken from active sinkholes about 1/4 mile south of the Heagy-Burry Park sinkhole. A contact between Hawthorn Group sand and sandy clay was identified during field investigations in abandoned quarries approximately 1.5 miles south of the Heagy-Burry Park sinkhole complex. The clayey units in this formation act as an aquiclude and cause the Floridan aquifer system to be under confined conditions in areas of Hawthorn occurrence. The high content of phosphates and clays, with associated radioactive particles, produces high counts (often > 200 counts per second) on a natural gamma log, which aids in formation identification (Davis 1996). Geophysical well logs in this area show that Hawthorn Group beds dip toward the east and northeast. The Hawthorn Group in this area ranges in thickness from a few feet in erosional remnants to an entire unit that is approximately 120 feet (Davis 1996). These relatively thick and impermeable sediments of the Hawthorn Group act as the principal confining beds that result in artesian pressure in the Floridan aquifer system.

2.5 POST-HAWTHORN GROUP DEPOSITS

2.5.1 Pliocene to Recent Series

Sands, silts, clayey sands, and clays, referred to generally as undifferentiated sands and clays, form a surface veneer over parts of the project area where they occur. Some geologists have suggested that these deposits range in age from Pliocene (or late Miocene) to Pleistocene and recent (Bermes et al. 1963, Leve 1966), yet recent studies (Miller 1986, Scott 1988, Hoenstine and Lane 1991) place the units in age ranging from Pliocene to Holocene.

Pliocene deposits are differentiated from the Hawthorn Group by the absence of phosphate within them (Leve 1966). These deposits are made up of interbedded clay and clayey sand, fine to medium grained, well sorted sand, shell, and soft limestone. The transition from the underlying Hawthorn Group to the Pliocene deposits is obvious in natural gamma logs, as gamma ray activity due to the radioactive phosphates present in the Hawthorn Group deposits are significantly higher (Scott 1988). This transition is usually marked by an unconformity consisting of coarse sands and phosphates.

Pleistocene and Recent deposits generally contain fine to coarse grained, loose sand, clayey sand, sandy clay, marl, shell, and clay. The lithology and texture of beds within these deposits vary both horizontally and vertically over short distances (Bermes et al. 1963, Fairchild 1972). Between the Pleistocene and Recent deposits and the underlying Pliocene deposits, there is no distinct transition (Leve 1966).

These post-Hawthorn Group (from approximately 5.3 mya to the present) deposits may summarily be described as containing varying percentages of clay and sand with occasional occurrences of quartz pebbles. This unit overlies the Hawthorn Group when present, and it is quite variable in thickness. In areas where the Hawthorn Group is missing, these sediments directly overlie the Ocala Group Limestone. In the vicinity of Orange Lake, these sands generally are less than 10 feet thick (Lane and Hoenstine 1991).

2.6 TOP OF THE OCALA LIMESTONE

Sinkholes are areas of localized land surface subsidence, or collapse, due to karst processes, which result in closed circular depressions of moderate dimensions (White and White 1987). They are formed by the subsidence or the collapse of surficial material into subsurface cavities in regions underlain by limestone and other rocks susceptible to dissolution by ground water. Within the project area, the prolific Floridan aquifer system is composed of porous and permeable carbonate rocks. The top of this aquifer system is made up of the Ocala Limestone, which is susceptible to dissolution by acidic surficial water with which it comes into contact. In the west and southwest of the project area where the Ocala Limestone is exposed, surficial dissolution and drainage occur. However, in the other areas of the Orange Lake basin where there is an overburden (Miocene Hawthorn Group and Plio-Pleistocene and Recent deposits) on the carbonates, subsurface dissolution takes place leading to karst topography characterized by sinkholes, caves, and underground drainage.

Since subsurface dissolution of the Ocala Limestone poses risks to the stability of surficial bodies of water and other infrastructure, it is important to map the surface of this unit. It would be most appropriate to determine such a surface by drilling wells throughout the project area and then analyzing the cores from such an endeavor. The time and budget for this study did not allow for such procedures. However, borehole geophysical logs obtained from SJRWMD (see Table 2-2) for the Orange Lake area were used to obtain the necessary subsurface data.

One type of probe lowered into existing boreholes was used to measure the response to changes in natural gamma radiation emitted from the formation that a borehole penetrates. The

Table 2-2. List of geophysically logged wells used for determining the top of the Floridan aquifer system (Ocala Limestone) and the thickness of the confining unit throughout most of the Heagy-Burry Park area

Well Identification Number	North Latitude (degrees, minutes, and seconds)	West Longitude (degrees, minutes, and seconds)	Total Depth (feet)	Elevation of the Top of the Ocala Limestone (ft, NGVD)	Thickness of confining unit (feet)
A-0456	29 27 20	82 08 01	82	-20.7	80
A-0686	29 29 17	82 09 48	86	-5.2	68
A-0687	29 28 42	82 09 32	82	-18	82
A-0715	29 29 06	82 09 50	199	-19.5	79
A-CCMH	29 29 07	82 09 50	199	-19.4	81
M-0057	29 22 33	82 05 04	172	35.9	24
M-0152	29 21 59	82 12 53	85	52	28
M-0154	29 23 43	82 10 05	40	26.7	38
M-0155	29 24 01	82 07 31	62	25	50
M-0156	29 24 01	82 07 34	115	25	50
M-0157	29 24 02	82 07 23	116	25	55
M-0164	29 28 53	82 15 55	129	90	60
M-0303	29 24 00	82 05 08	100	-18.3	78.3
M-0304	29 24 58	82 06 34	101	40	33
M-0305	29 27 10	82 13 55	159	46	104
M-0345	29 25 38	82 12 31	100	25	41
M-0347	29 26 45	82 14 16	201	25	36
M-0351	29 26 56	82 12 50	54	22	38
M-0361	29 25 24	82 09 34	84	10	52
M-0364	29 24 25	82 10 37	210	30	44
M-0367	29 26 22	82 13 18	218	97	60
M-0368	29 26 21	82 12 59	316	39	39
M-0370	29 26 32	82 13 10	324	50	50
M-0371	29 26 05	82 13 11	235	95	55
M-0372	29 26 06	82 13 08	445	30	95
M-0374	29 27 00	82 13 00	158	30	38
W-2719	29 27 47	82 17 35	–	115	–

Source of well logs: Division of Ground Water Programs, SJRWMD 1996 probe recorded changes in lithology versus depth. The clay units of the Hawthorn Group in this area produce high peaks on the gamma ray log while low peaks are registered by the carbonates of the Floridan aquifer and quartz sands of the surficial and intermediate aquifers. Correlation of the logs developed throughout the area was made, and the top of the Ocala Limestone surface which corresponds to the gamma ray's high peak at the bottom of the Hawthorn Group clay was determined. Based on interpretation of these geophysical logs, the elevation of the top surface of the Floridan aquifer system (Ocala Limestone) ranges from -10 to 110 ft, NGVD, in the study area (see Figure 2-2).

2.7 THICKNESS OF POST-EOCENE DEPOSITS

The Orange Lake subbasin, which encompasses Heagy-Burry Park, occurs in parts of Florida's Central Valley and Fairfield Hills geomorphologic regions. The Central Valley occupies the north, east, and south parts of the project area, while the Fairfield Hills occupy the western part of the project area. In general, elevations range from 70 to 100 ft, NGVD, and from 120 to 150 ft, NGVD, respectively, for these regions (Hoenstine and Lane 1991). However, the elevation of the Central Valley in the project area displays little variation, ranging only from 50 to 60 ft, NGVD, and in this area it is characterized by flat-bottomed lakes and prairies and erosional remnants of the plateau. Orange Lake and Heagy-Burry Park occur in this area. In the western part of the project area, where the Fairfield Hills occur, denudation of the Miocene Hawthorn sediments on the Ocala arch has laid bare a limestone terrain (Pirkle and Brooks 1958).

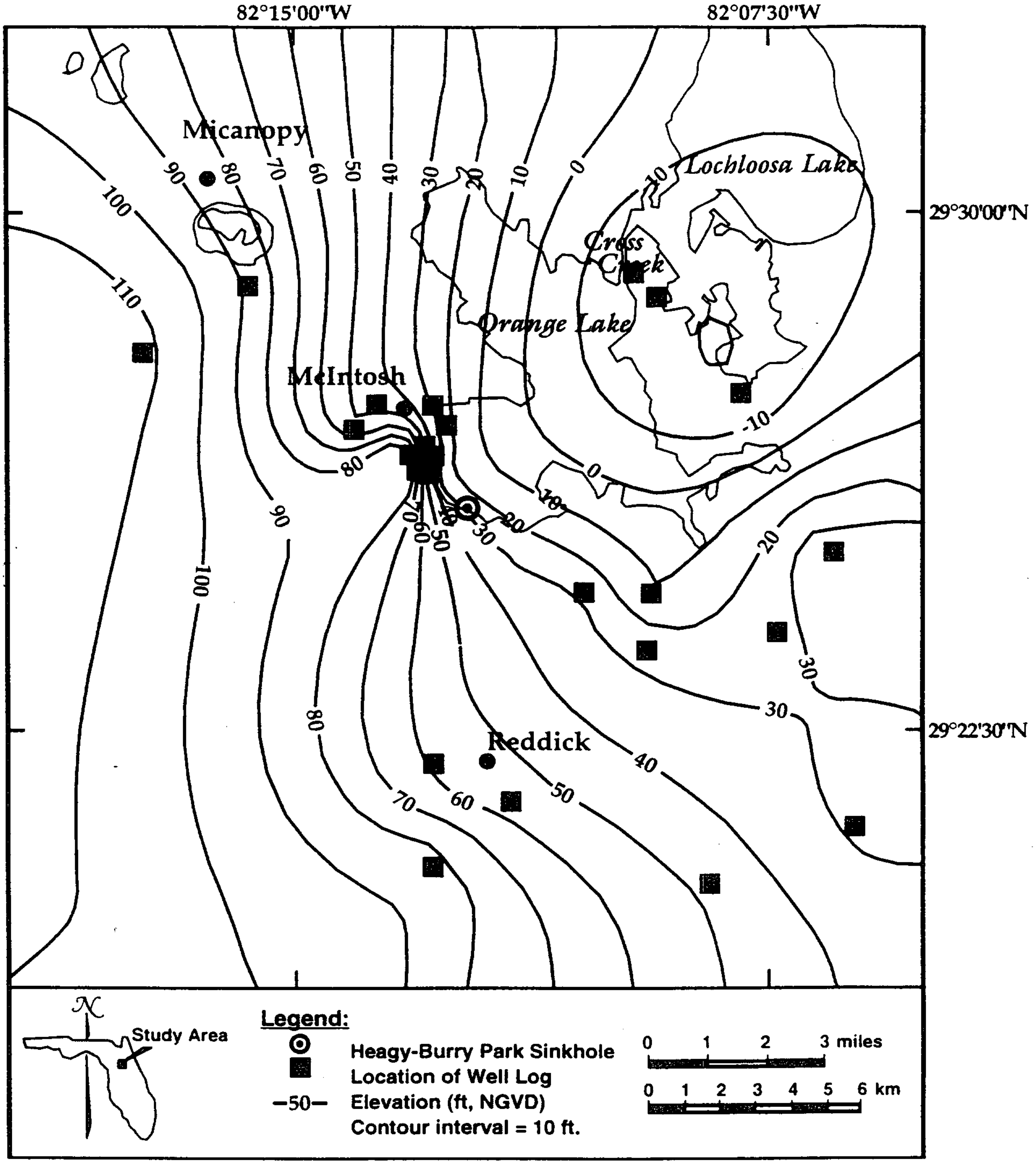


Figure 2-2. Top of the Ocala Limestone in the project area

Hawthorn Group sediments are present throughout the area east of the Fairfield Hills, and they dip gently and become thicker towards the northeast. Plio-Pleistocene clayey sands rest unconformably on the Hawthorn units. These Hawthorn Group sediments and Plio-Pleistocene clayey sands form a confining unit over the Floridan aquifer system. Gamma logs of wells (Table 2-2) scattered throughout the Heagy-Burry Park area were used to map most of the thickness of this overburden. From the combination of field observations and geophysical well log information, the confining unit thickness was determined to range from about 5 ft to just over 100 ft.

3.0 HYDROLOGY

3.1 SURFACE WATER

3.1.1 Orange Creek Basin

Lochloosa and Orange lakes are the principal surface-water bodies within the project area (Figure 2-1). These lakes are flat-bottomed and respectively occupy the Lochloosa and Orange subbasins. Along with Newnans Lake and Orange Creek, they make up the Orange Creek Basin (see Figure 3-1). These subbasins are connected to each other and contribute runoff to Orange Creek, which is a tributary of the Ocklawaha River. This river eventually flows into the St. Johns River.

3.1.2 Lochloosa Lake

The Lochloosa Lake subbasin occupies an area nearly 75 square miles (mi^2), and its major drainage feature, Lochloosa Creek, drains about 51 mi^2 of rural lands to the northwest of the lake (Robison et al. 1993). The Lochloosa Creek watershed receives runoff from Orange Heights, Campville, and Grove Park. The watershed receives flow in the City of Hawthorne from Iron Spring and Sulphur Spring.

The lake itself has a surface area of approximately 5,600 acres, a mean depth of about 7 ft, and a maximum depth of 11 ft (Langeland 1982). The lake shoreline is characterized primarily by a relatively direct transition from lake to cypress wetland. It is a eutrophic, soft water lake (Canfield 1981) with dense stands of aquatic macrophytes at times. Water drains slowly to

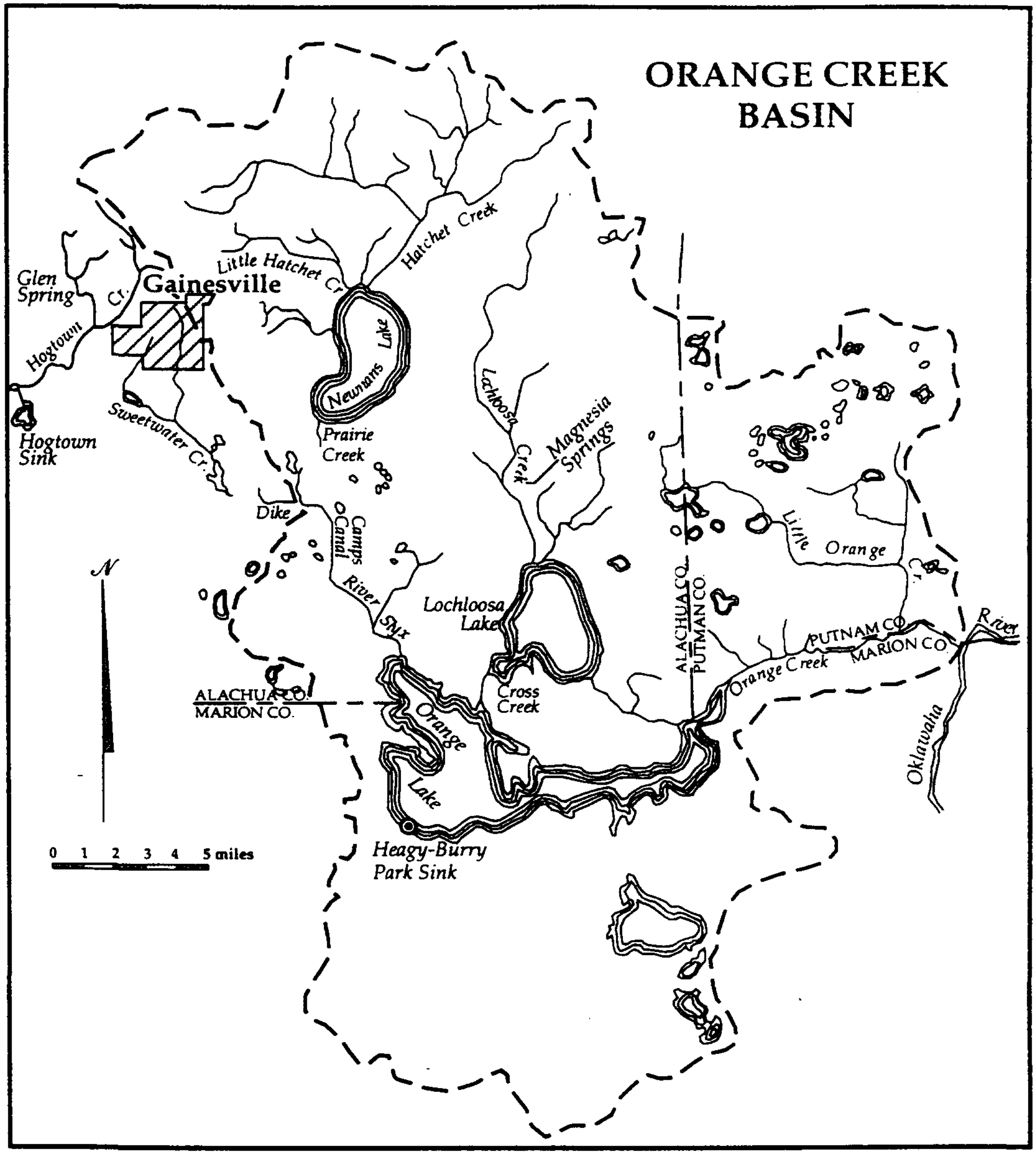


Figure 3-1. Orange Creek Basin (based on Clark et al. 1964)

Orange Creek through Lochloosa slough during high lake levels. However, Lochloosa Lake's main outflow is through Cross Creek to Orange Lake.

3.1.3 Orange Lake

Orange Lake is the larger of the two surface water bodies in the project area, and its subbasin has an area of 127 mi^2. Rowland (1957) reported that the Orange Lake watershed covers 210,000 acres. There are two main surface water inflows to this basin (see Figure 3-1). One is at its northwest end from the River Styx, which receives discharge from Camps Canal, which diverts the outflow of Newnans Lake through Prairie Creek from its natural destination to Alachua Sink on the north side of Paynes Prairie. The other is through Cross Creek, where exchange of water occurs between Lochloosa and Orange lakes down to 54.5 ft, NGVD, which is the elevation of the highest point of the channel bed. Generally, flow is from Lochloosa to Orange Lake, but at very high water stages the flow may be reversed.

Orange Lake drains surficially through Orange Creek at its east end into the Ocklawaha River, a tributary of St. Johns River. Since April 1963, the outlet at the bridge on U.S. Highway 301 has been controlled by a 160 foot-long concrete dam, the crest of which is at an elevation of 58 ft, NGVD, with a notch in the center at 55.5 ft, NGVD (USGS 1995).

Orange Lake is shallow, with water depths ranging mostly from 7 to 12 ft at the normal lake level of 58 ft, NGVD (Jessen 1972). Deevey (1988) reported that the residence time of the lake water was 0.95 years. Through the years, the water level of the lake has fluctuated substantially due to drought conditions. According to data collected by the USGS, the lake level reached a low of 50.06 ft, NGVD, in August 1956 and a high of 61.50 ft, NGVD, in November

1941 (see Table 3-1). Consequently, large changes in the surface area of the lake also have occurred due to such lake stage fluctuations. Moreover, estimates of the surface area of Orange Lake vary widely, depending on whether the measurements were based on the entire area of lake and marsh, the area covered by lake water, or the area of open surface water.

Table 3-1. Storage capacity of Orange Lake versus water-surface elevation

Water-Surface Elevation (ft, NGVD)	Capacity (acre-feet)
61.50 (flood stage, November 1941)	80,000
58.00 (normal stage)	52,000
55.00 (notch stage)	26,000
50.06 (drought stage, August 1956)	4,000

Source: Modified from Jessen 1972

Some maps based on aerial photographs delineate only the area of open waters. Such aerial photograph measurements are easily and accurately measured. The total area of the lake and marsh at an average lake level of about 58.0 ft, NGVD, is estimated to be 16,500 acres (Table 3-2).

Correspondingly, the capacity of Orange Lake also fluctuates substantially with changes in water depths. Such shallow lakes with gently sloping sides and extensive surrounding marshes experience tremendous volumetric shifts with changing surface elevation. Table 3-1 shows how the capacity of Orange Lake changes relative to changes in water-surface elevation.

Table 3-2. Area of Orange Lake at 58.0 ft, NGVD, lake elevation

Area (acres)	Category
7,800	open water
5,800	marsh, west of US 301
13,600	lake and marsh west of US 301
2,000	marsh and pasture, east of US 301
15,600	total present lake and marsh
900	cropland on drained muck soils east of US 301
16,500	total lake, marsh, and muck soil

Note: Calculations for area are based on aerial photographs taken in January, 1964.

Source: Jessen 1972

3.2 GROUND WATER HYDROLOGY

3.2.1 Aquifer Systems

The ground water system around the Orange Lake Heagy-Burry Park area is made up of three aquifer systems: the surficial aquifer system; the intermediate aquifer system; and the upper part of the Floridan aquifer system (Lane and Hoenstine 1991). Correlations between the geologic formations and the hydrostratigraphy in the vicinity of Orange Lake are shown in Table 3-3.

3.2.2 Surficial Aquifer System

Relatively thick sequences of undifferentiated Pliocene and Pleistocene sand and clayey sand sediments make up the surficial aquifer system. This uppermost water bearing unit generally

Table 3-3. Generalized hydrogeologic units in the vicinity of Orange Lake

Series	Geologic Unit	Hydrostratigraphic Unit	Description
Post-Miocene	Undifferentiated terrace, marine and fluvial deposits	Surficial aquifer system	Discontinuous sands, clayey sands, and shell beds (0-20 ft thick).
Miocene	Hawthorn Group	Intermediate aquifer system or intermediate confining unit	Variable clay, marl, sands, shell, carbonates, and phosphates (0-190 ft thick).
Eocene	Ocala Limestone	Floridan aquifer system	Tan to cream, soft, fossiliferous limestone, grainstone to wackestone
	Avon Park Formation		Tan to brown, hard dolostone and limestone

Source: Adapted from Lane and Hoenstine 1991

follows the local topography, but the saturated thickness can vary considerably. Furthermore, the saturated thickness is influenced by local rainfall and evapotranspiration conditions. Over most of the project area, the undifferentiated sands and clays form only a surface veneer of sediments about 10 ft thick with the thickest sections in the Fairfield Hills region. Recharge to this aquifer system is primarily from percolation of direct rainfall through surface soils. In times of minimal rainfall, the lakes contribute recharge to the surficial aquifer. The water obtained from the surficial aquifer in this area is not used for potable purposes. Surface depressions and the aquifer serve as storage for recharge to Orange and Lochloosa lakes and the underlying aquifers.

Ground water flow within the surficial aquifer system is generally horizontal in the direction of decreasing gradients, especially in areas where there is a continuous lower confining unit. Nonetheless, vertically downward movement of water may take place where there are breaches in the confining unit, through thin layers of the confining unit, or higher permeability zones. The magnitude of the vertical and horizontal fluxes are controlled by the water gradient and hydraulic conductivities in the respective directions (Annable et al. 1994). Vertical and lateral water movement partly account for discharge from the surficial aquifer. Other discharge occurs by means of evapotranspiration and pumping from wells.

3.2.3 Intermediate Aquifer System

The intermediate aquifer system of the Miocene Hawthorn Group is composed of highly variable beds of limestone, sand, clays, shells, and sandy clays. The sediments in this area have variable but generally low hydraulic conductivities (Clark et al. 1964). Boniol et al. (1993) report a median value of vertical hydraulic conductivity taken from core tests of 0.0037 ft/day. The zones of sands and clayey sands have the highest potential for water production and may be identified by low counts on a natural gamma log. Such units, lenses, or pockets of laterally discontinuous layers supply water for some outdoor self-supply use. The water is usually of questionable quality due to mineralization from the clays and phosphates. Wells in the area also run dry under drought and continued pumping conditions.

An upper semiconfining unit of variable thickness at the top of the Hawthorn Group separates the surficial aquifer from the intermediate aquifer. Also, a semiconfining unit of variable thickness underlying the intermediate aquifer is hydraulically connected to the top of the Floridan aquifer by means of vertical leakage and breaches (Clark et al. 1964). The clays act as aquitards and are the principal hydraulic barriers at the top and the bottom of the intermediate aquifer system.

The section of the intermediate aquifer system that underlies Orange Lake consists entirely of the semiconfining units. The intermediate aquifer system is thickest in the Fairfield Hills but nonexistent in the far southwestern and western edge of the project area, where erosion of the Central Ridge exposes the Upper Floridan aquifer carbonates. The Hawthorn Group sediments dip towards the east and northeast, thickening to as much as 120 ft.

Recharge to the intermediate aquifer system is mainly from the overlying surficial aquifer system wherever the latter occurs. In this study area, the thick sequence of surficial aquifer material in the Fairfield Hills contributes most of the recharge to the intermediate aquifer system. The rest of the area has only a veneer of surficial aquifer material that stores a relatively small amount of water available to recharge the intermediate aquifer system. When recharge occurs, it is by means of leakage through the upper confining unit of the Hawthorn Group and where the confining unit is breached or absent.

Discharge from the intermediate aquifer is in the form of vertically downward leakage through the lower confining unit in the Hawthorn Group and also where the confining unit has been breached into the Floridan aquifer system. Cavities in the Upper Floridan aquifer also form hydraulic connections between the intermediate and Upper Floridan aquifers (Clark et al. 1964). Further discharge also occurs through pumping from wells.

3.2.4 Floridan Aquifer System

The Floridan aquifer system, which is the principal source of water for the communities within this project area, is part of an extensive artesian aquifer system that extends throughout Florida and parts of Georgia, Alabama, and South Carolina (Miller 1986). This aquifer system is generally divided into four hydrologic units that do not coincide necessarily with the boundaries of time stratigraphic units or rock types but rather with vertical variations in permeability (Miller 1986). These hydrologic units are an upper zone of high permeability, a middle confining zone of low permeability, a lower zone of low-to-high permeability, and a lower confining unit. For the purposes of this project, the two uppermost hydrologic units of the Floridan aquifer system are mostly dealt with. It is here that interaction between surface processes, ground water, and carbonates is most intimate.

The Ocala Group Limestone and the upper third of the Avon Park Formation form the Upper Floridan aquifer in this area. Actually, the Ocala Group Limestone occurs at or near land surface in the west and southwest of the project area. These carbonates are highly permeable and hence susceptible to dissolution by acidic surface waters. The high permeability is due to a combination of well developed primary and secondary porosity of the limestone in the Upper Floridan aquifer. The secondary porosity has resulted from the formation of dissolution cavities within the limestone of the Upper Floridan aquifer. Hence, caves and enlarged joints and fractures have developed.

The middle confining unit is composed of lower permeability beds of limestone and dolomite than those above and below it. It extends approximately from the middle to the upper third of the Avon Park Formation, although in some locations it extends upward to the base of the Ocala Limestone. In the project area, this unit is considerably thin. It pinches off and only extends from the east to about midway beneath Orange Lake.

The water quality of the Floridan aquifer system is usually considered good for public and domestic consumption. The communities that have grown throughout this area, i.e., Citra, Cross Creek, Orange Lake, Micanopy, and McIntosh, are supplied with water for potable use and other purposes primarily from the Floridan aquifer system. The water is hard, calcium bicarbonate type, commonly free of bacteriologic contamination. The mineral content usually increases with depth (Faulkner 1973). Chloride concentrations are generally below 40 milligrams per liter (Rohrer 1984).

In the west and south of this study area where the Upper Floridan aquifer is mostly unconfined, recharge is basically from precipitation. Recharge is also acquired from the intermediate aquifer system through the lower confining unit of the Hawthorn Group. Dissolution cavities in the Upper Floridan aquifer that have collapsed form hydraulic connections to the overlying intermediate aquifer, and they also can form connections through the Hawthorn Group into the surficial aquifer system. Direct hydraulic connections exist between the bottom of Orange Lake and the Upper Floridan aquifer at the lake's southwest corner. This is at the Heagy-Burry Park sinkhole complex, where the confining unit underneath the lake has been breached following the dissolution of limestone. Here, surface lake water has been estimated to recharge the Upper Floridan aquifer through the sinkhole complex by as much as 37.6 cubic feet per second (cfs) (Haller and Hoyer 1992). However, Wilson and Spechler (1992) observed that approximately 11 cfs of lake water was lost to the Upper Floridan aquifer through cavernous openings near Heagy-Burry Park.

Discharge from the Upper Floridan aquifer assumes various forms. It is a very prolific aquifer and therefore serves as source of potable water for the communities in this area. Most pumping wells tap into this aquifer to obtain water for a variety of uses. Other discharge is through upward leakage where breaches occur and also through evapotranspiration in the extreme west and southwest corners of the project area where the Upper Floridan aquifer is at or near the surface.

3.3 POTENTIOMETRIC SURFACE

The potentiometric surface of an aquifer is that surface connecting all points to which water will rise in tightly cased wells. Within the study area, where the Upper Floridan aquifer is confined, the contour lines of equal elevation of the potentiometric surface represent the elevation to which water will rise in a tightly cased well, and where the Upper Floridan aquifer is not confined, the contours indicate the elevation of the water table. Potentiometric surface contours reveal the direction of ground water flow since it is at right angles to the contours and towards a decreasing hydraulic head. Recharge and discharge are important phenomena that determine potentiometric heads in aquifer systems.

For the purposes of this project, it was deemed necessary to work with potentiometric surfaces spanning the most recent decade (1985 to 1995). USGS potentiometric surface maps from 1985 through 1995 were evaluated for absolute maximum and minimum water levels. For the last decade in the project area, the September 1988 map was the highest potentiometric surface (see Figure 3-2), and the May 1991 map was the lowest potentiometric surface (see Figure 3-3).

There is as much as an 8-foot head difference between the high September 1988 surface and the low May 1991 surface (see Figure 3-4). The potentiometric surface gradient varies throughout the project area, becoming progressively steeper from the southwest corner of Orange Lake towards the northeast of Lochloosa Lake. In the south-southwest and west-northwest, gradients are less steep, and the elevation of the potentiometric surface is relatively lower. Furthermore, there are remarkable differences in the orientation of the potentiometric surface contours between the September 1988 high and the May 1991 low levels. Flow lines on the September 1988 contours (Figure 3-2), which represent maximum water levels, generally exhibit a divergent phenomenon towards the south and southwest. Flow lines on the May 1991 contours (Figure 3-3), which represent minimum water levels, on the other hand exhibit a convergent phenomenon towards the southwest. Field investigations (e.g., observations of strand lines in caves south of Heagy-Burry Park) and comparisons of the potentiometric surface and head difference maps (Figures 3-2, 3-3, and 3-4) indicate a transition from a confined system to an unconfined system as one traverses the project area from the northeast to the south and southwest (Moffor 1996). The Hawthorn Group (confining unit), which occurs throughout much of this part of the state, thickens from the southwest towards the northeast. This has been verified by examining various geophysical well logs from this area (Moffor 1996). The higher potentiometric surface in the northeast is indicative of the presence of the confining unit in that area. It may be observed that low transmissivities correlate with the higher potentiometric surfaces and higher

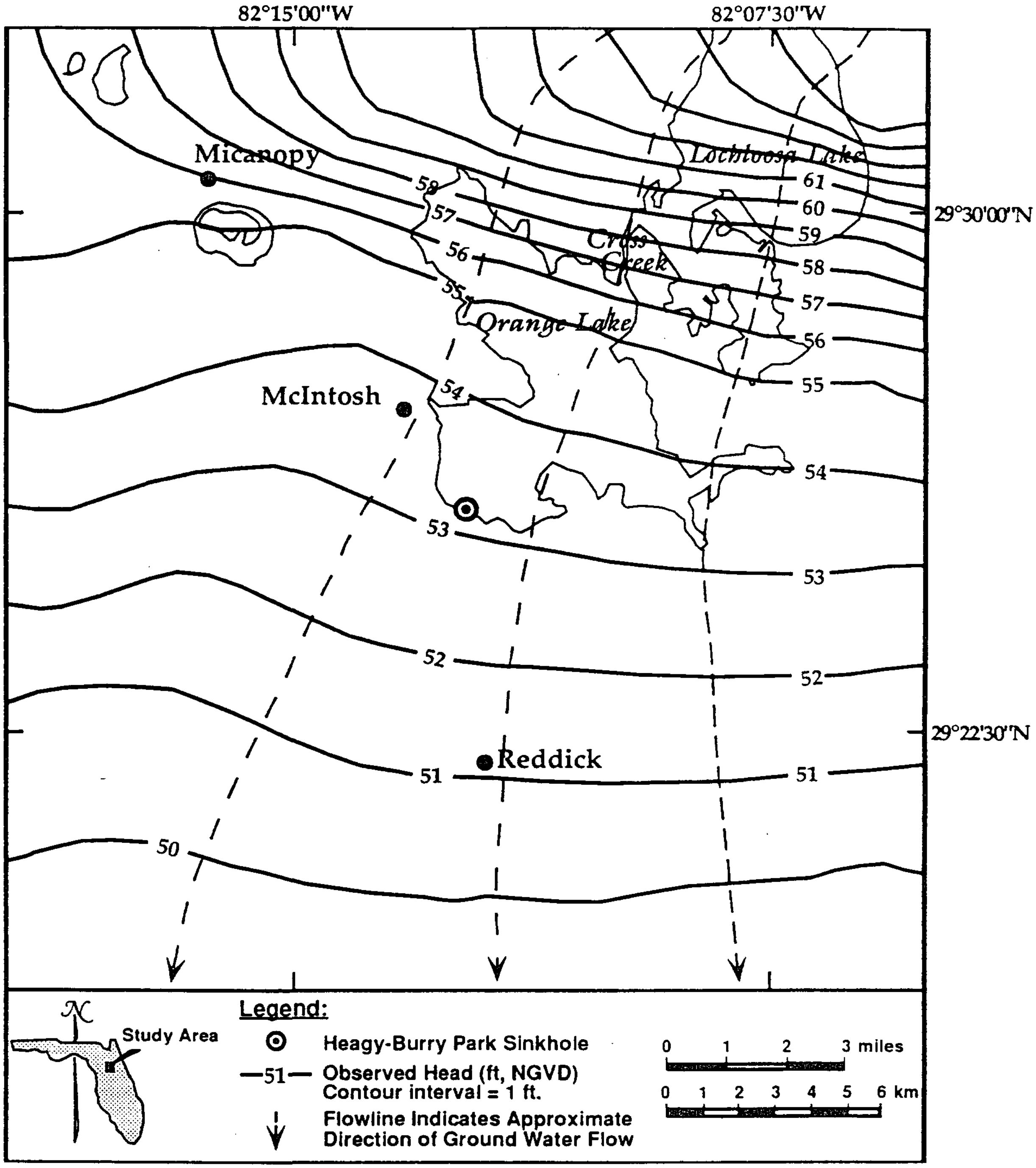


Figure 3-2. Potentiometric surface in the Upper Floridan aquifer in September 1988

Note diverging flow lines.

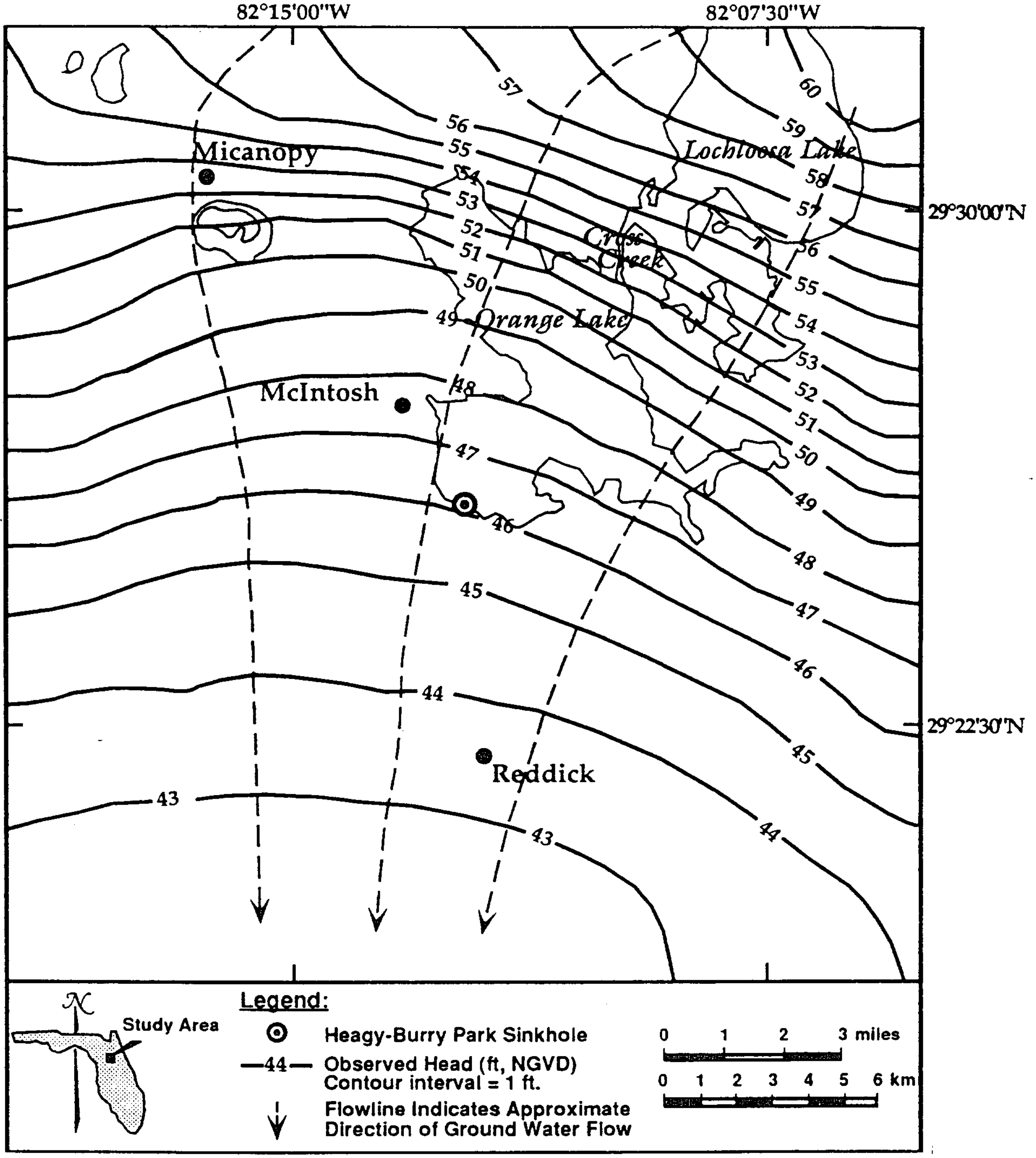


Figure 3-3. Potentiometric surface in the Upper Floridan aquifer in May 1991

Note converging flow lines.

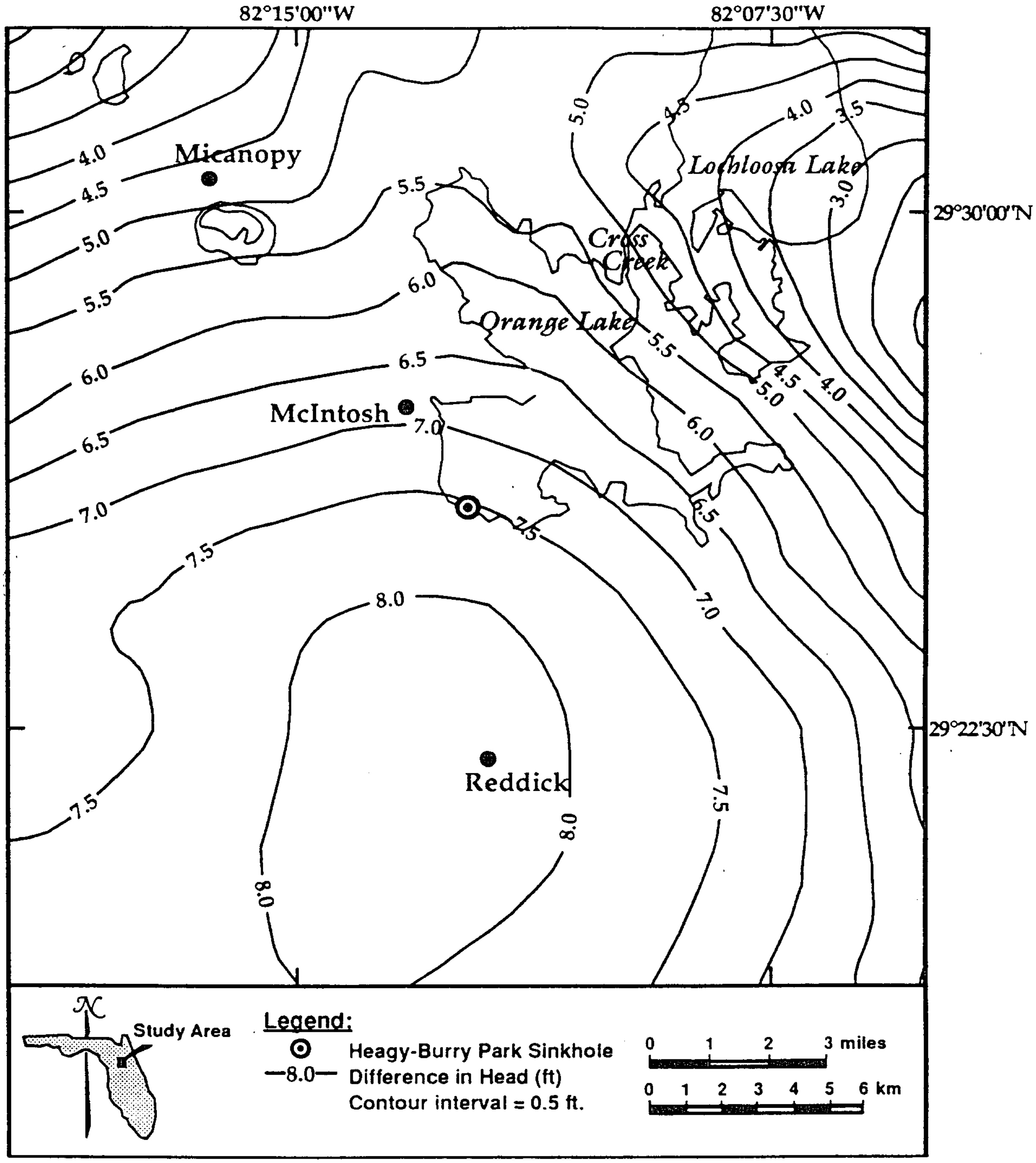


Figure 3-4. Difference in potentiometric heads between September 1988 (maximum level) and May 1991 (minimum level) for the 1985-1995 period

gradients towards the north and northeast while the converse would occur in the south and southwest. Recharge to the Upper Floridan aquifer in the project area also follows a pattern consistent with the orientation of the hydrogeological features of the area. In the south and southwest, where the confining unit (Hawthorn group) is relatively thinner and transmissivities are higher, recharge to the Upper Floridan aquifer is higher than in the east and northeast, where a thick confining unit and lower transmissivities occur.

Difference maps between the top of the Ocala Limestone (Figure 2-2), and the maximum and minimum potentiometric surfaces were developed (see Figures 3-5 and 3-6). These difference maps further confirm the confined and unconfined regions within the project area. Moffor (1996) noted the boundary between these regions as a demarcation line where contours shift westward with higher water levels and eastward with lower water levels. The September 1988 and May 1991 demarcation lines indicate where the Upper Floridan aquifer maximum and minimum potentiometric surfaces intersect the top of the Ocala Limestone (see Figure 3-7).

It should be emphasized here that this demarcation line is based only on data between 1985 to 1995. For the extreme hydrologic conditions during November 1941 (maximum water levels) and August 1956 (minimum water levels), the line would shift west and east, respectively, and therefore likewise will enlarge the area of concern or zone in which the wetting capability is most active (Moffor 1996).

West of the demarcation line, the potentiometric head of the Upper Floridan aquifer is generally below the top of the Ocala Limestone, but it is above the top of the limestone east of the line. A water table thus occurs in the unconfined west and southwest, while there is a

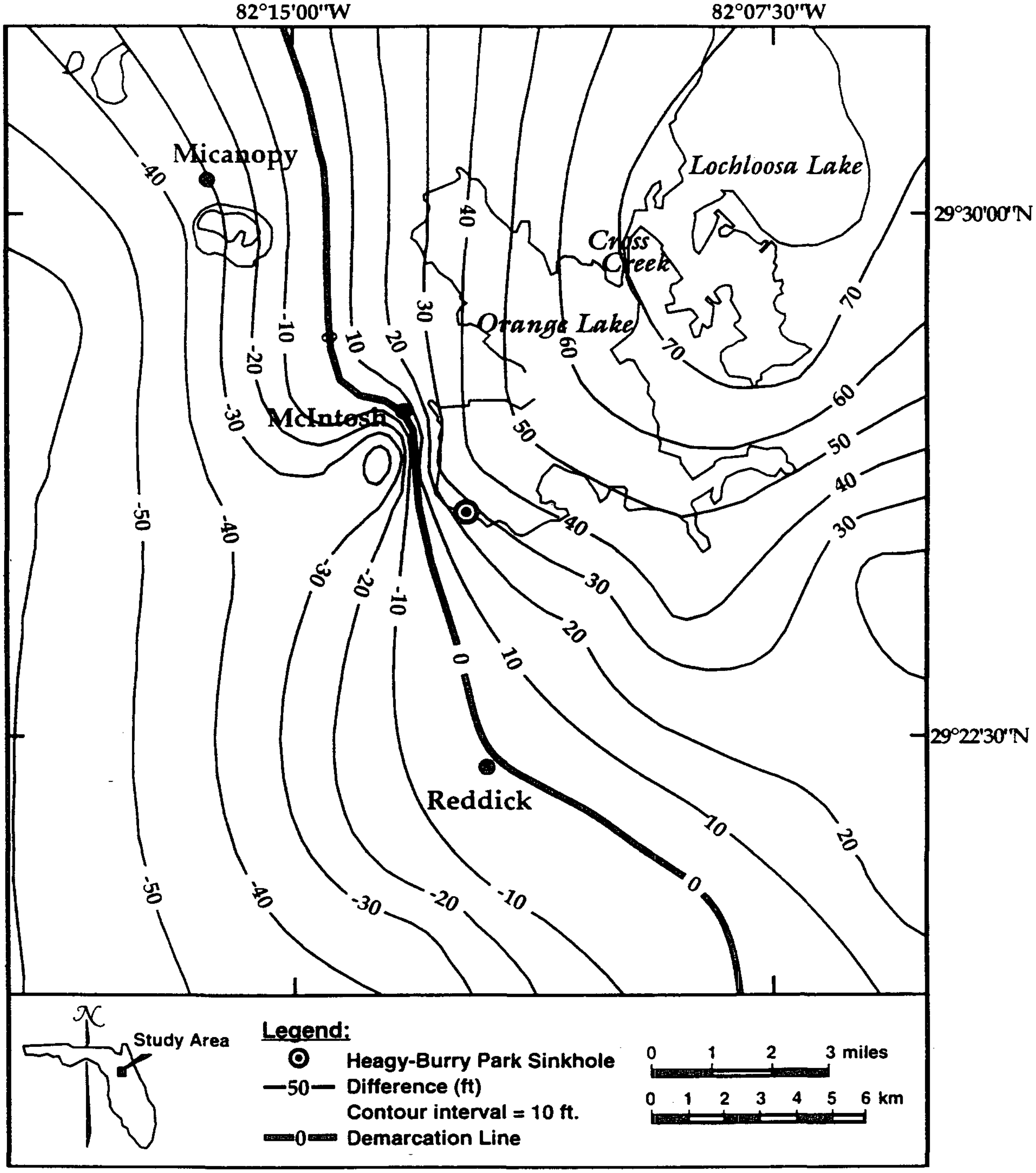


Figure 3-5. Difference between the maximum potentiometric surface during the period from 1985 to 1995 (September 1988) and the top of the Ocala Limestone

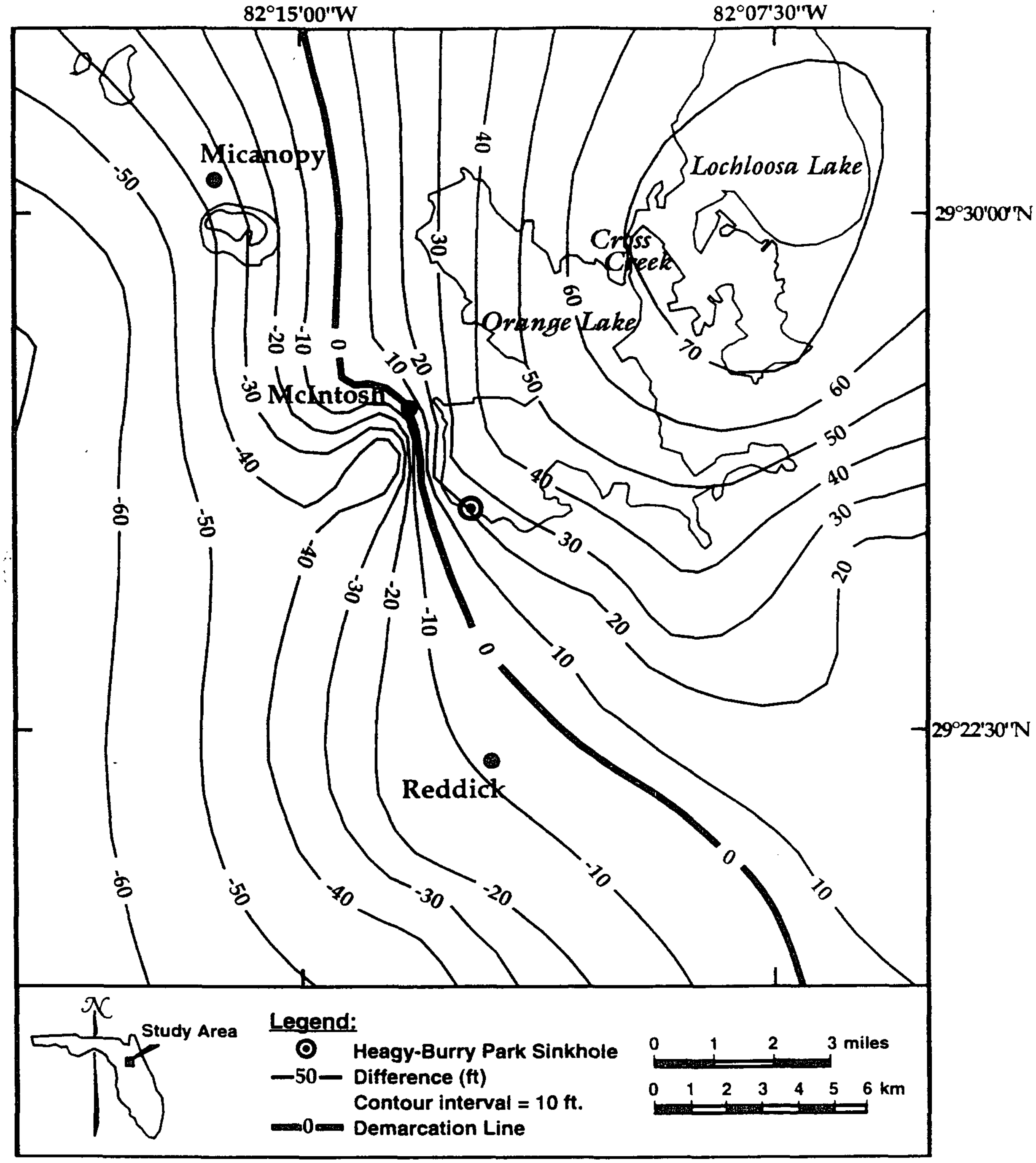


Figure 3-6. Difference between the minimum potentiometric surface during the period from 1985 to 1995 (May 1991) and the top of the Ocala Limestone

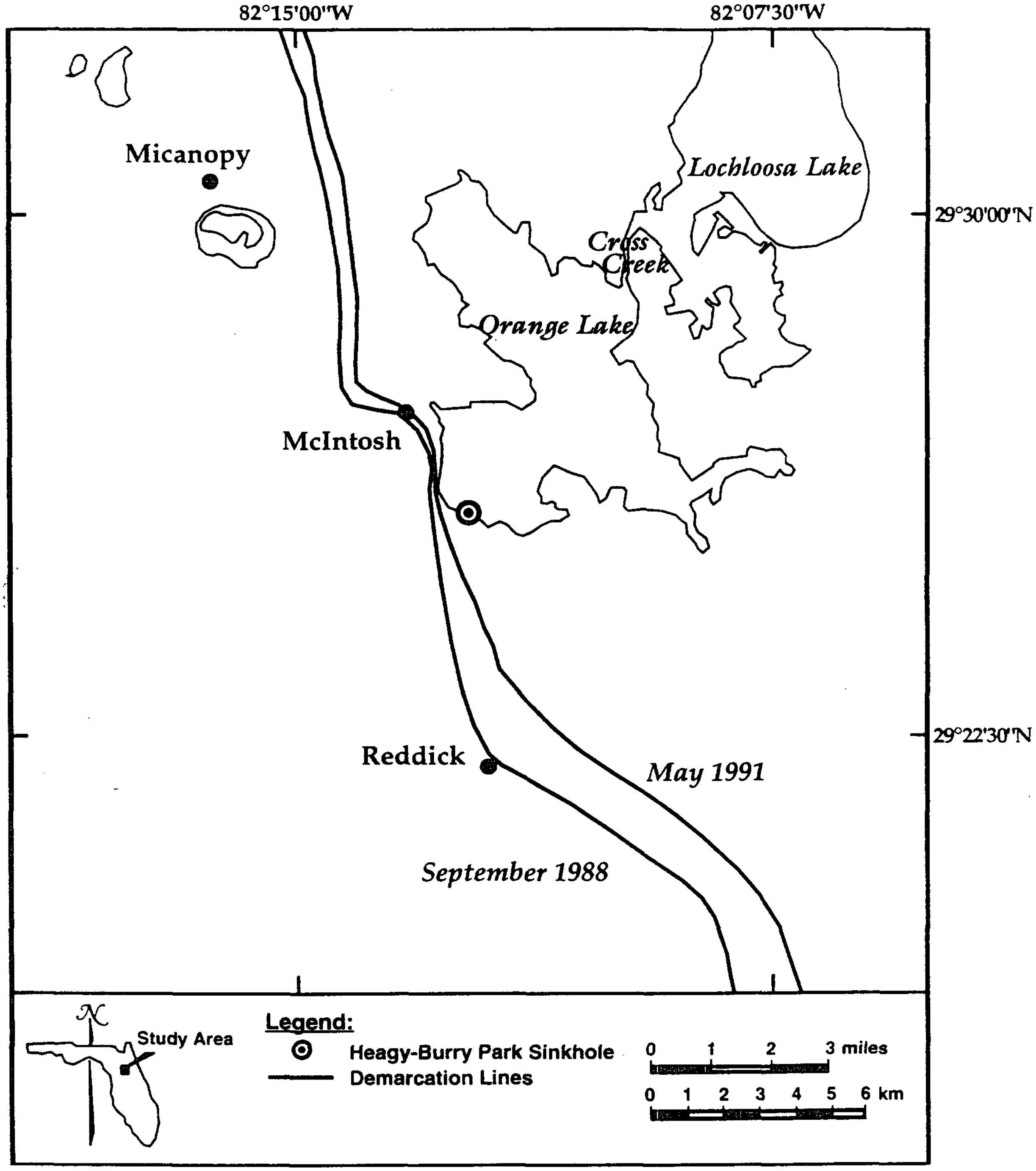


Figure 3-7. Demarcation lines where the potentiometric surfaces intersected the top of the Ocala Limestone in September 1988 (maximum level) and May 1991 (minimum level)

potentiometric surface where the Upper Floridan aquifer is under confined conditions to the east and northeast of the line in the study area.

As expected, differences between the demarcation lines (Figure 3-7), as derived from the difference maps (Figures 3-5 and 3-6), indicate substantial fluctuations of potentiometric surfaces within the Ocala Limestone. Such fluctuations have been confirmed from field observation in caves within abandoned limestone quarries approximately 1.5 miles south of Orange Lake. Water levels in large caves within the quarry complex were noted to change with the seasons, as evidenced by water-level marks on the cave walls. Such vertical fluctuations normally result in more active solution of carbonate rock near the water table and to a slight depth beneath it (Pirkle et al. 1959).

Subsequently, formation of underground karst features resulting from solution of carbonate rocks has lead to a large number of sinkholes in this area. It is suggested that the area of high susceptibility for karst formation is the region that lies between the demarcations for the water table given by the differences between the maximum and minimum Upper Floridan aquifer potentiometric surface and the top of the Ocala Limestone. Field observations in the vicinity and south of the Heagy-Burry Park (particularly near the Jai Lai Fronton) have confirmed this to be true (Moffor 1996). Some of these sinkholes are active, and some large sinkholes occur about 3/4 mile south within the region mentioned. An inventory of sinkhole features, ground surface depressions, and slumping features in the area has been carried out using a global positioning system (GPS) unit to obtain the positions of such features (see Table 3-4). As noted by Moffor (1996) and Davis (1996), most of the points representing these features are in the vicinity of the

Table 3-4. Sinkhole locations around Heagy-Burry Park, Orange Lake, Florida

Number of Co-ordinates	North Latitude (degrees, minutes, and seconds)	West Longitude (degrees, minutes, and seconds)	Approximate Dimensions	
			Diameter (feet)	Depth (feet)
1	29 25 25	82 09 27	9	3
2	29 25 23	82 09 33	45	3
3	29 24 57	82 12 04	20	6
4	29 24 58	82 12 04	80	7
5	29 24 45	82 12 06	50	4
6	29 25 03	82 12 03	150	25
7	29 24 56	82 11 58	90	10
8	29 24 59	82 12 02	50	15
9	29 25 06	82 12 05	200	25
10	29 25 10	82 12 14	40	4
11	29 25 35	82 12 29	150	30
12	29 25 32	82 12 31	80	18
13	29 25 31	82 12 37	120	30
14	29 25 32	82 12 33	30	20
15	29 25 31	82 12 32	100	30
16	29 25 36	82 12 38	30	25
17	29 25 34	82 12 20	120	30
18	29 25 38	82 12 25	80	6
19	29 25 37	82 12 20	100	8
20	29 25 37	82 12 23	100	10
21	29 25 21	82 12 22	120	10
22	29 25 26	82 12 23	90	25
23	29 25 27	82 12 28	80	15
24	29 25 21	82 12 28	150	35
25	29 25 17	82 12 27	120	27
26	29 25 15	82 12 25	50	18
27	29 25 23	82 12 32	120	25
28	29 25 18	82 12 32	60	25
29	29 25 17	82 12 32	45	18
30	29 25 17	82 12 29	160	30
31	29 25 11	82 12 27	90	12
32	29 25 08	82 12 24	40	6
33	29 25 14	82 12 35	120	10

Heagy-Burry Park sinkhole complex (see Figure 3-8). Ground penetrating radar (GPR) profiles at the park may indicate the presence of cavities.

3.4 HYDROGEOLOGY

Two hydrogeologic cross-sections through the project area are located on Figure 3-9. The first, a general cross-section from west to east through the Heagy-Burry Park sinkhole, shows the relationship of the land surface, top of the Ocala Limestone, and potentiometric heads (see Figure 3-10). The second cross-section shows these hydrogeologic relationships from the southwest to the northeast across the project area (see Figure 3-11) (Moffor 1996).

The irregularly shaped Fairfield Hills form a topographic high at approximately 210 ft, NGVD, west of the Orange Lake plain. The average elevation of Orange Lake is approximately 58 ft, NGVD. The Orange Lake plain marks the base level to which erosional remnants of the current topographical escarpment have been reduced.

The maximum elevation of the top of the Ocala Limestone within the study area is about 110 ft, NGVD, beneath the Fairfield Hills. Towards the extreme west and southwest, erosion has left the carbonates bare, allowing for direct and relatively high recharge to the Upper Floridan aquifer. The Ocala Limestone dips considerably towards the east but much more towards the northeast where there are thicker units of confining rocks. Such conditions provide for higher potentiometric heads in the confined northeast and lower heads in the unconfined west and south-west.

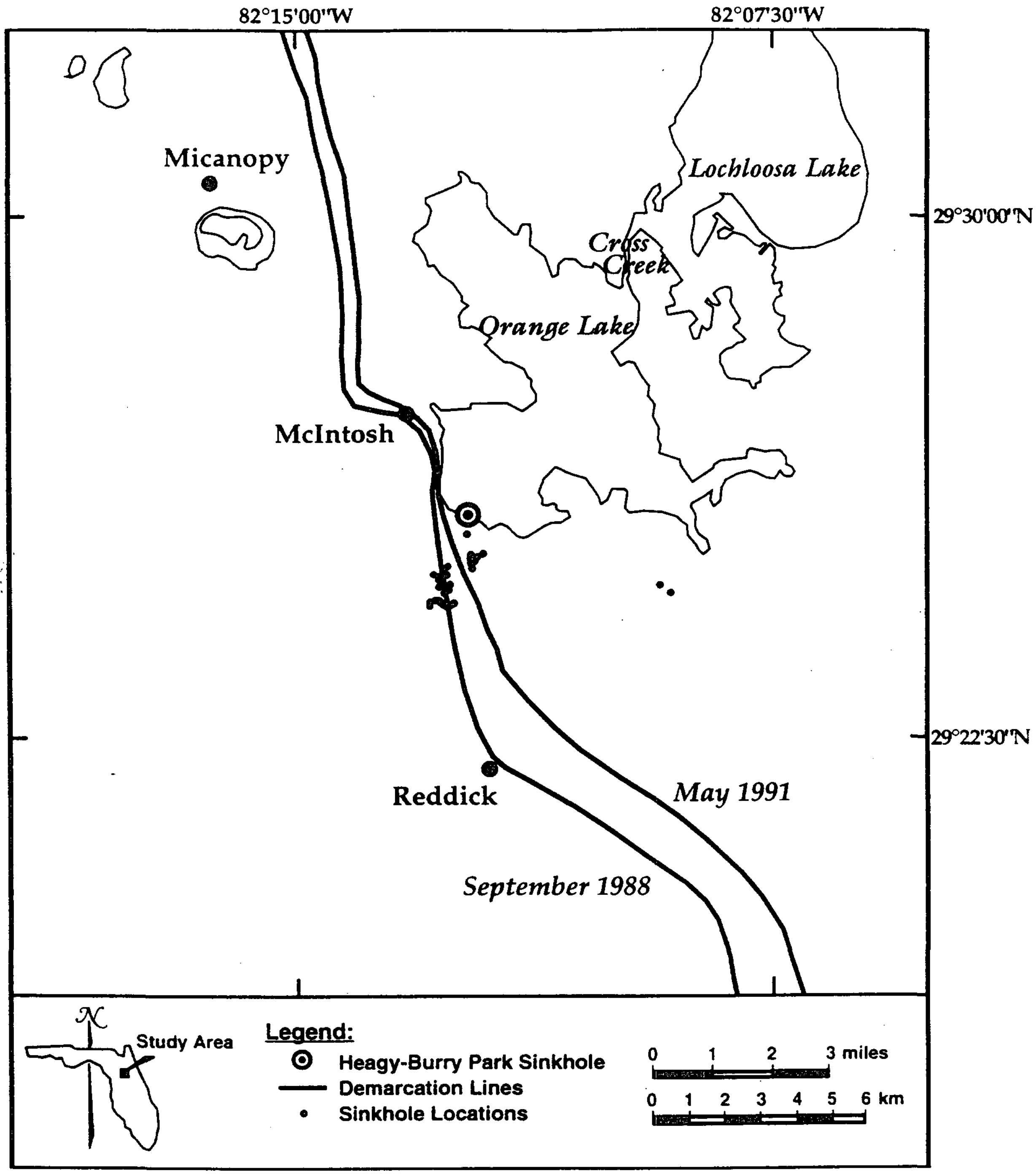


Figure 3-8. Sinkhole locations around Heagy-Burry Park and water-table demarcation lines in the Upper Floridan aquifer for September 1988 (maximum level) and May 1991 (minimum level)

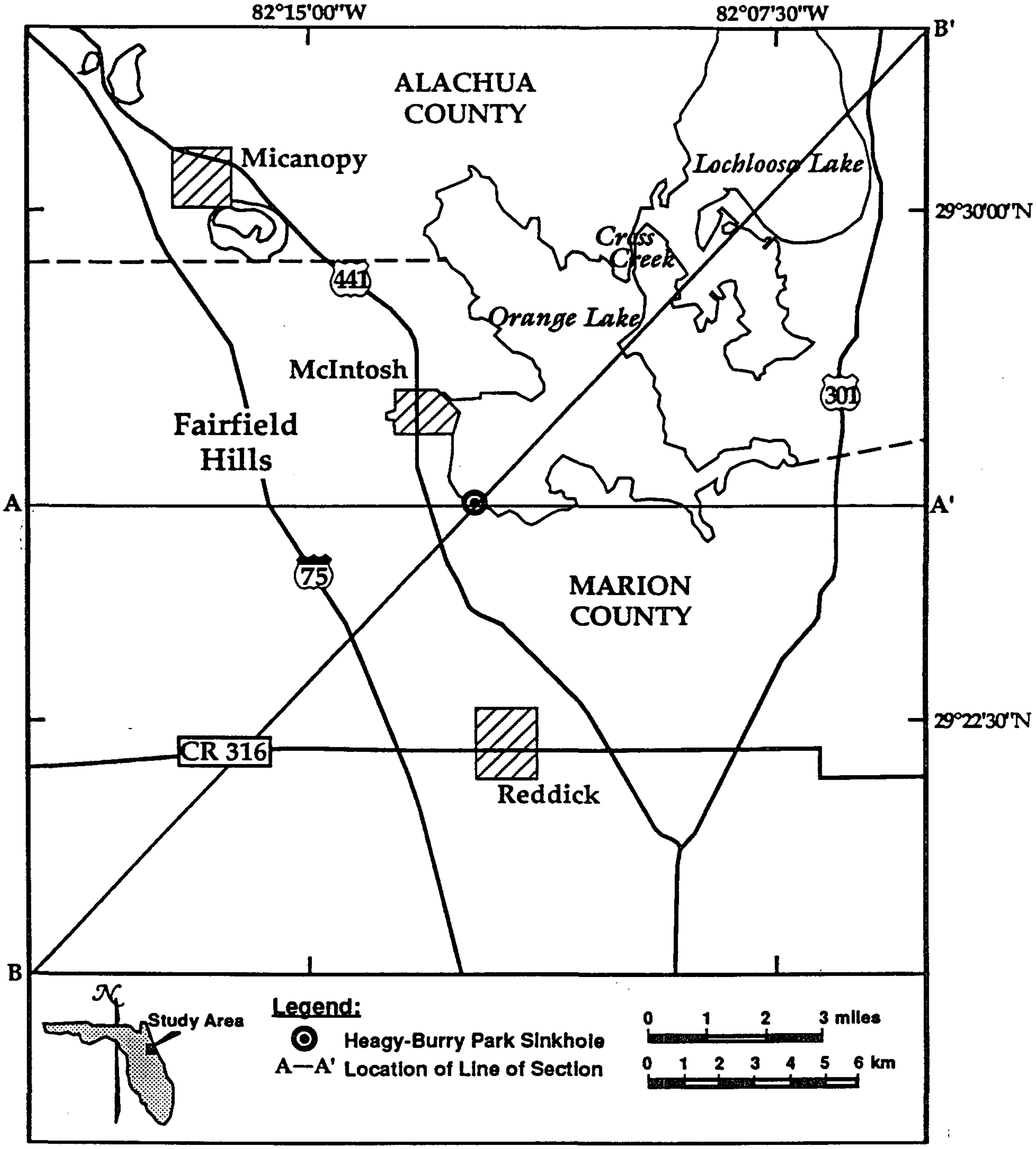


Figure 3-9. Locations of hydrogeologic cross-sections A-A' and B-B'

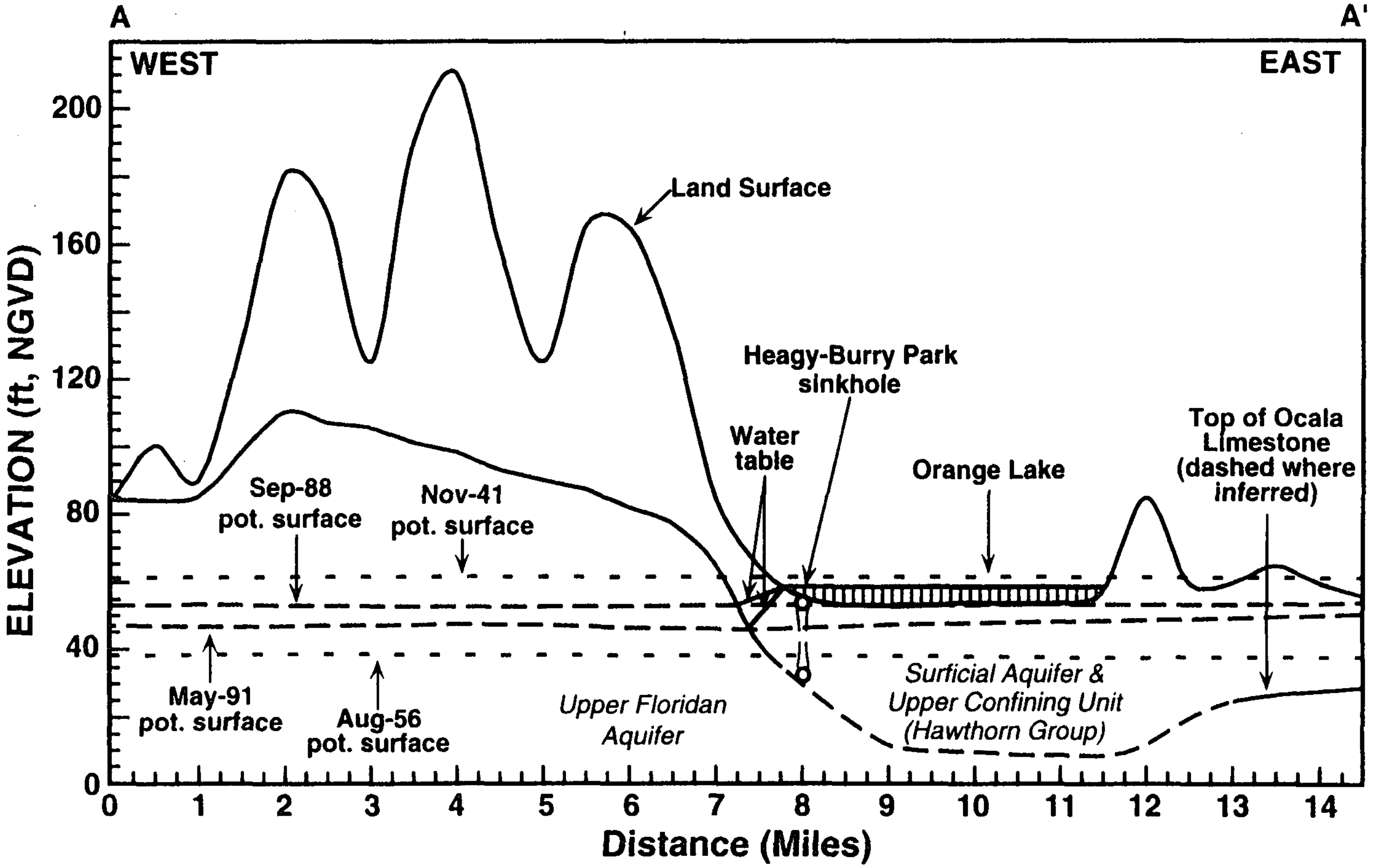


Figure 3-10. West-East cross-section (A-A′) showing land surface, top of the Ocala Limestone, and the potentiometric surface

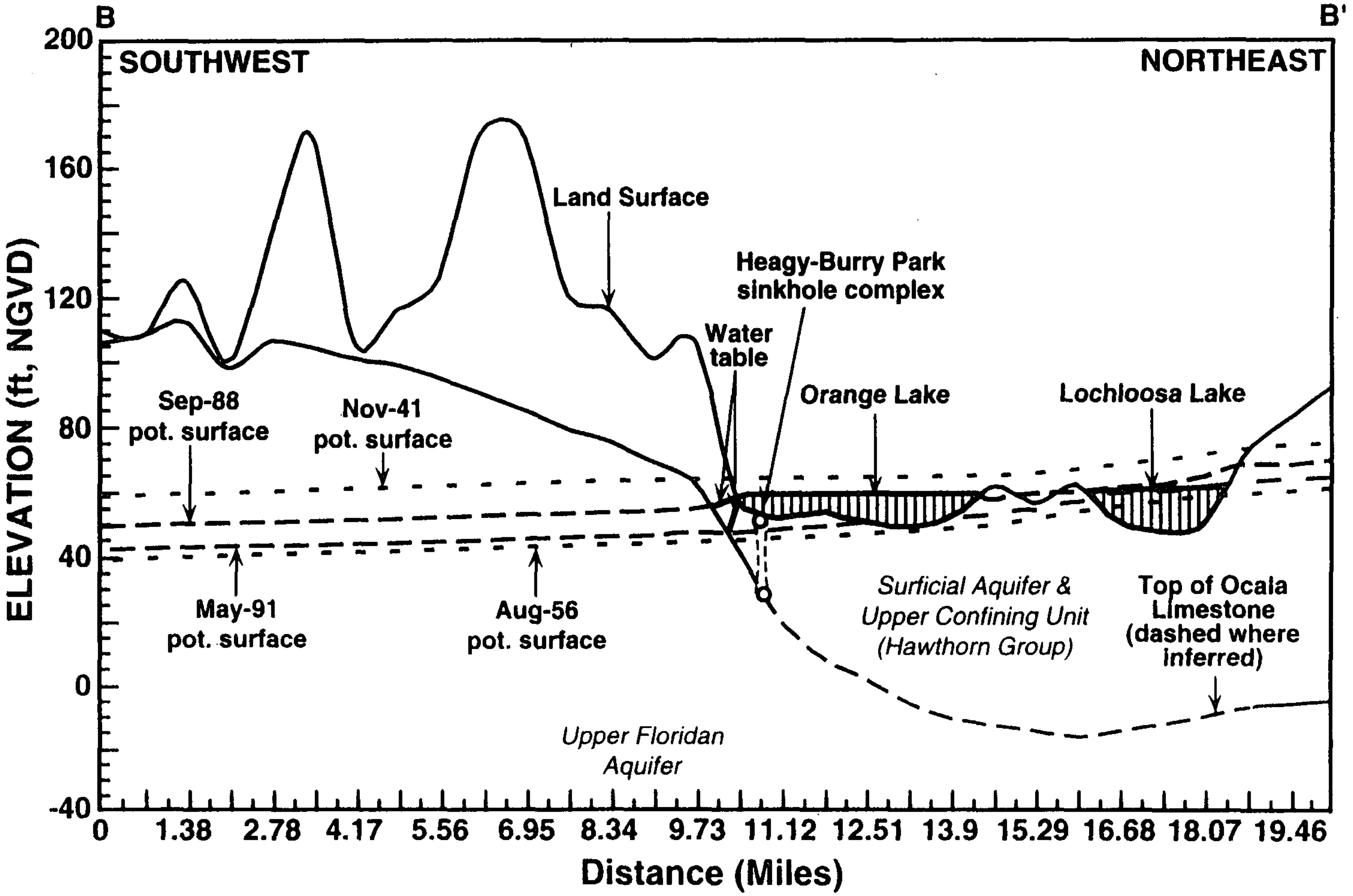


Figure 3-11. Southwest-Northeast cross-section (B-B′) showing land surface, top of the Ocala Limestone, and the potentiometric surface

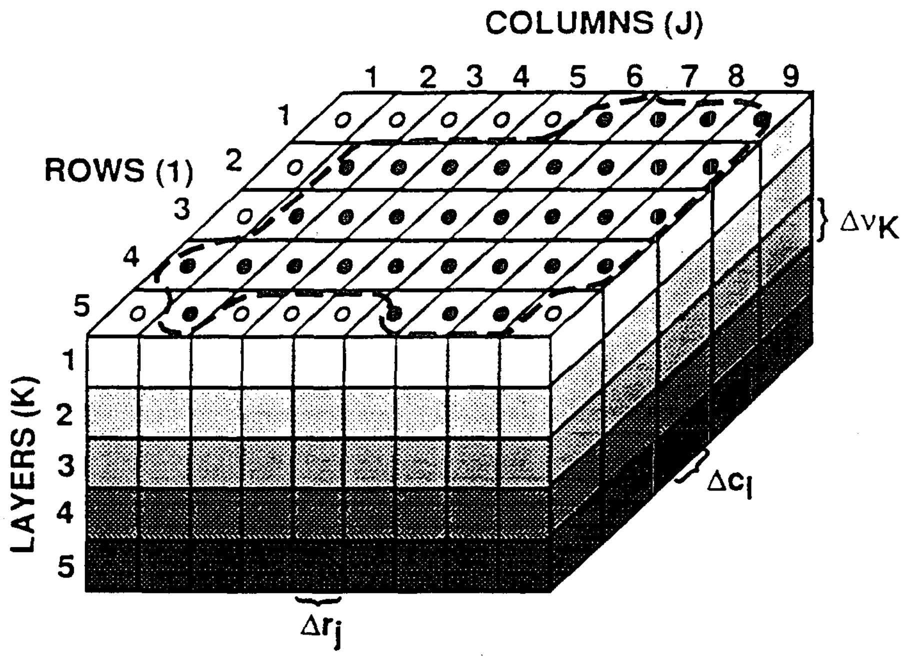
4.0 GROUND WATER MODEL

4.1 MODEL SELECTION

4.1.1 Model Code

The USGS modular three-dimensional finite-difference ground water code MODFLOW (McDonald and Harbaugh 1988) was selected to model the ground water system in the area. As described in this chapter, a ground water model was developed and calibrated by simulating the May 1991 potentiometric surface (Figure 3-3), and then the model was verified by simulating the September 1988 potentiometric surface (Figure 3-2).

In MODFLOW, an aquifer system is discretized with a mesh of blocks called cells, the locations of which are described in terms of rows, columns, and layers (see Figure 4-1). An i,j,k indexing system is used, and within each cell, the hydraulic head is calculated at a point called a node, which is at the center of each block. MODFLOW PC/EXT Version 1.31 dated 3/93 was used to perform the simulations. The preprocessor PREMOD (GeoTrans 1988) was used to prepare some of the input files, along with a text editor, and version 2.1 of the postprocessor POSTMOD (Williams 1988) was used to write output files in an x-y-z format. Version 1.0 of MODVIEW (Durden 1994), a software program that calculates statistical results for arrays such as drawdown and head and which uses a visual, color-coded scheme to indicate different ranges in values in such arrays, was used to help calibrate the model.



— —	Aquifer Boundary
●	Active Cell
o	Inactive Cell
Δr_J	Dimension of Cell Along the Row Direction. Subscript (J) Indicates the Number of the Column.
Δc_I	Dimension of Cell Along the Column Direction. Subscript (I) Indicates the Number of the Row.
Δv_K	Dimension of Cell Along the Vertical Direction. Subscript (K) Indicates the Number of the Layer.

Source: McDonald and Harbaugh 1988.

Figure 4-1. Discretized hypothetical aquifer system

4.1.2 Model Packages

The basic (BAS), block-centered flow, version 2 (BCF2), well (WEL), river (RIV), evapotranspiration (EVT), general-head boundary (GHB), recharge (RCH), strongly implicit procedure (SIP), and output control option (OC) packages were used in the model. The BCF2 package (McDonald et al. 1991) was used in order to simulate the drying and rewetting of cells in layer one in part of the area bounded by the demarcation lines (Figure 3-7), which delineate the transient location of the westward extent of the water table in the Hawthorn Group.

4.2 CONCEPTUALIZATION AND AQUIFER PARAMETERS

4.2.1 Hydrogeologic Units

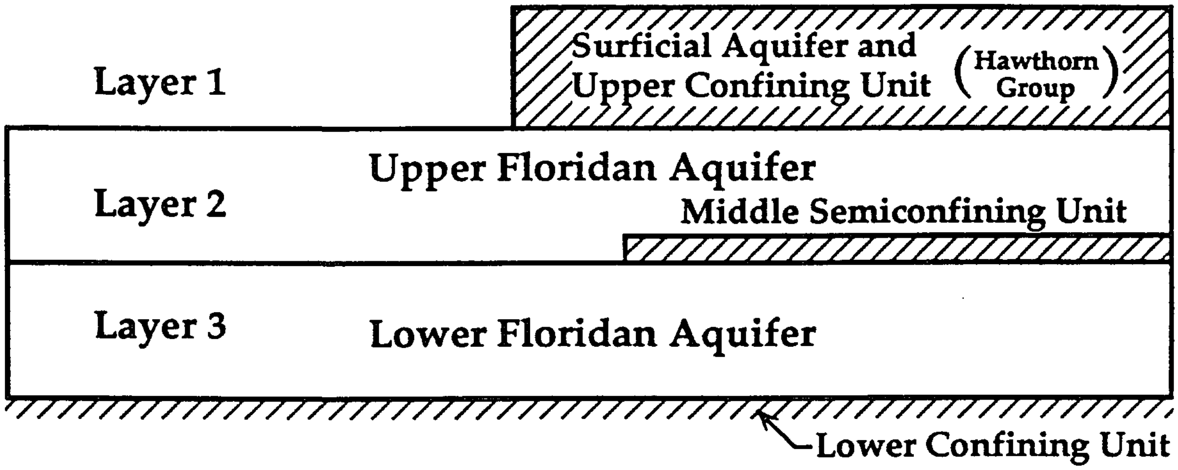
As noted in Chapters 2 and 3, the Hawthorn Group, which overlies the Upper Floridan aquifer, is present throughout the project area. In the southern part of the area, the Hawthorn Group is very karstic, and a large number of sinkholes are present. In the central and western parts of the area, the middle semiconfining unit that separates the Upper Floridan aquifer from the Lower Floridan aquifer does not exist (Miller 1986). In this area, Miller combined the Upper and Lower Floridan aquifers into one unit called the "Upper Floridan aquifer." For modeling purposes in this study, however, the Lower Floridan aquifer was considered to be a separate unit through the study area and well-connected with the Upper Floridan aquifer in the area in which the middle semiconfining unit does not exist. This is consistent with the modeling approaches used in this and/or adjacent areas by Bush and Johnston (1988), Krause and Randolph (1989), Motz et al. (1995), and Tibbals (1990).

Accordingly, the hydrogeologic system presented in Chapter 3 was considered to consist of three layers, or aquifer units, separated by confining units (see Figure 4-2). Layer one represents the surficial aquifer and the upper confining unit (Hawthorn Group) for the Floridan aquifer system. Layer two represents the Upper Floridan aquifer, which is confined in the northeastern part of the area and unconfined everywhere else. The intersection of the water table in the Upper Floridan aquifer with the Hawthorn Group separates the confined and unconfined parts of the Upper Floridan aquifer (Figure 3-7). Layer three represents the Lower Floridan aquifer.

4.2.2 Discretization

The study area was discretized into 35 rows and 35 columns that range in size from 100 feet to 5,000 feet (see Figure 4-3 and Table 4-1). This grid resulted in the model area being 73,500 feet by 73,500 feet. To model the sinkhole complex, the main sinkhole at Heagy-Burry Park was simulated in the center of the grid (row 18, column 18) with dimensions 100 ft by 100 ft. Also, two adjacent cells (row 18, column 17 and row 19, column 18) with dimensions 100 ft by 150 ft were used to simulate the other sinkholes that are adjacent to the main sinkhole. From the center of the grid, the dimensions were increased by a factor of 1.2 to 1.5. This range was selected to simulate better the impact of the sinkholes in the surrounding area and to cover an area as large as possible.

Constant head cells were assigned to layer one in the northeastern part of the area between Orange and Lochloosa lakes and the boundaries of the model. Cells in layer one were active in



Note: Conceptualization extends from West to East through the model area, and it is not drawn to scale.

Figure 4-2. Conceptualization of the hydrogeologic system in the model area

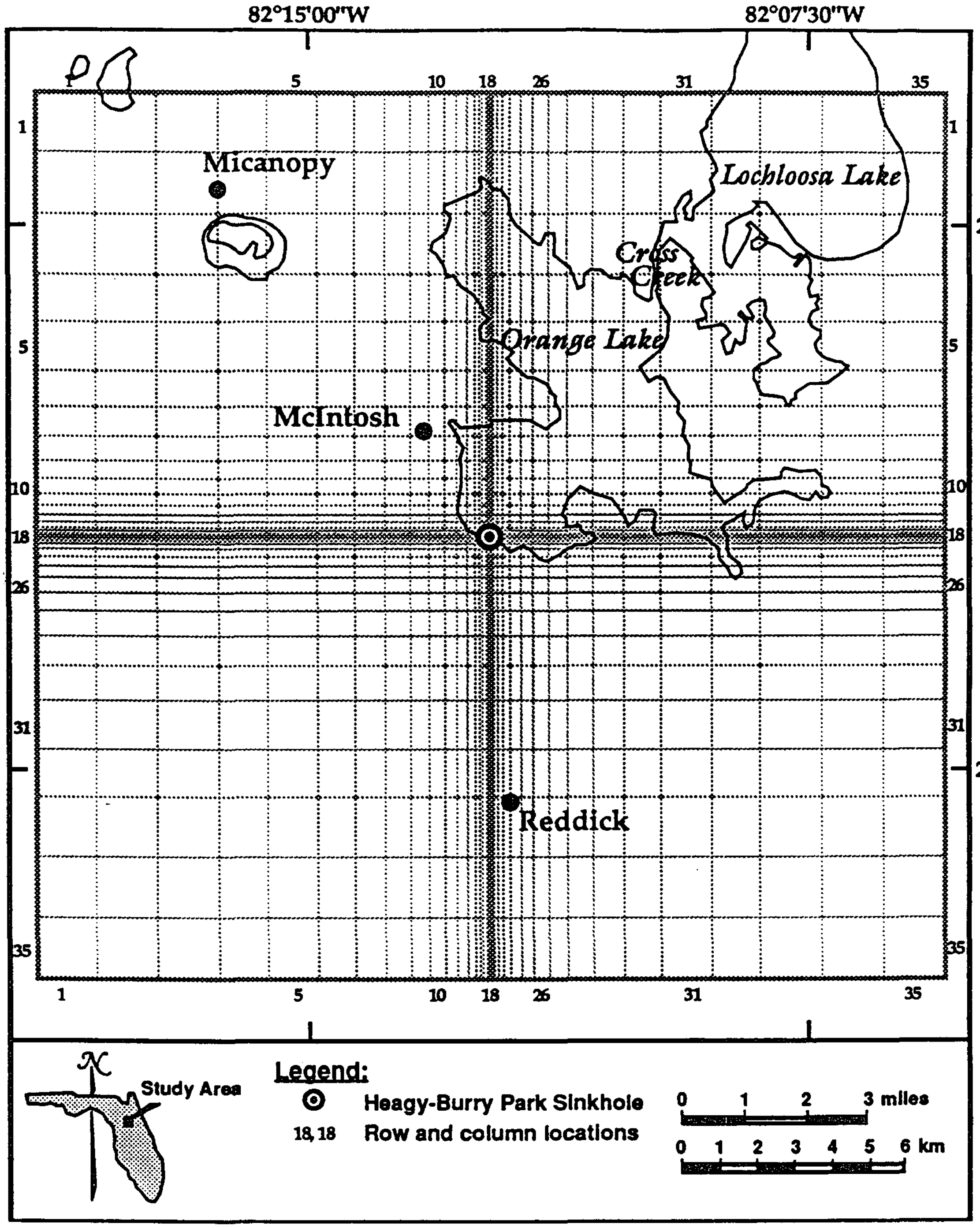


Figure 4-3. Discretization of the model area

Table 4-1. Dimensions of rows and columns in the MODFLOW model

Column Number	Width of Column (ft)	Row Number	Height of row (ft)
1-3 and 33-35	5000	1-3 and 33-35	5000
4-5 and 31-32	4000	4-5 and 31-32	4000
6 and 30	3000	6 and 30	3000
7 and 29	2500	7 and 29	2500
8 and 28	2000	8 and 28	2000
9 and 27	1500	9 and 27	1500
10 and 26	1250	10 and 26	1250
11 and 25	1000	11 and 25	1000
12 and 24	800	12 and 24	800
13 and 23	600	13 and 23	600
14 and 22	400	14 and 22	400
15 and 21	300	15 and 21	300
16 and 20	200	16 and 20	200
17 and 19	150	17 and 19	150
18	100	18	100

the model area west and south of Orange Lake and east of the demarcation lines (Figure 3-7) in which the Upper Floridan aquifer is confined. Cells in layer one were inactive in the area west of the demarcation lines (Figure 3-7) in which the Upper Floridan aquifer is unconfined. In layers two and three, the boundary cells were general head boundaries (see section 4.2.7), and all of the other cells in these layers were active cells. Heads in the part of layer one that was assigned constant head cells were based on a regression relation between land-surface elevation and depth to the water table (Motz et al. 1995).

4.2.3 Aquifer Parameters

The May 1991 simulation was run as a steady-state simulation, with one stress period and one time step equal to 1.0 day. Layer one was unconfined, and the value of the hydraulic conductivity in layer one was assumed to be $K_1 = 5.0 \times 10^{-3}$ ft/day to represent the relatively low hydraulic conductivity of most of this unit (Motz et al. 1995). The bottom elevation of the aquifer was an array generated based on logs for 25 wells (Figure 2-2), and the vertical leakance, or V_{cont1} in MODFLOW, was an array that was a calibration parameter. Starting values for V_{cont1} were based on Motz et al. (1995).

Layer two was treated as a confined/unconfined layer with a constant saturated thickness at each node. Spatially, the transmissivity was an array that was changed during the calibration. Starting values for transmissivity were based on Motz et al. (1995). The aquifer top elevation was an array equal to the elevation of the bottom of layer one. The values of V_{cont2} for layer two represent the leakance of the middle semiconfining unit. In the eastern part of the study area, where the middle semiconfining unit is present (see Figure 4-4), V_{cont2} was assigned a value of 1.0×10^{-5} day^{-1}. In the western part of the study area, where the middle semiconfining unit is absent, the value of V_{cont2} was assigned a value of 1.0×10^{-2} day^{-1}. Both these values were based on Motz et al. (1995).

Layer three was completely confined, and the transmissivity T_3 was set equal to 200,000 ft^2/day, based on Motz et al. (1995).

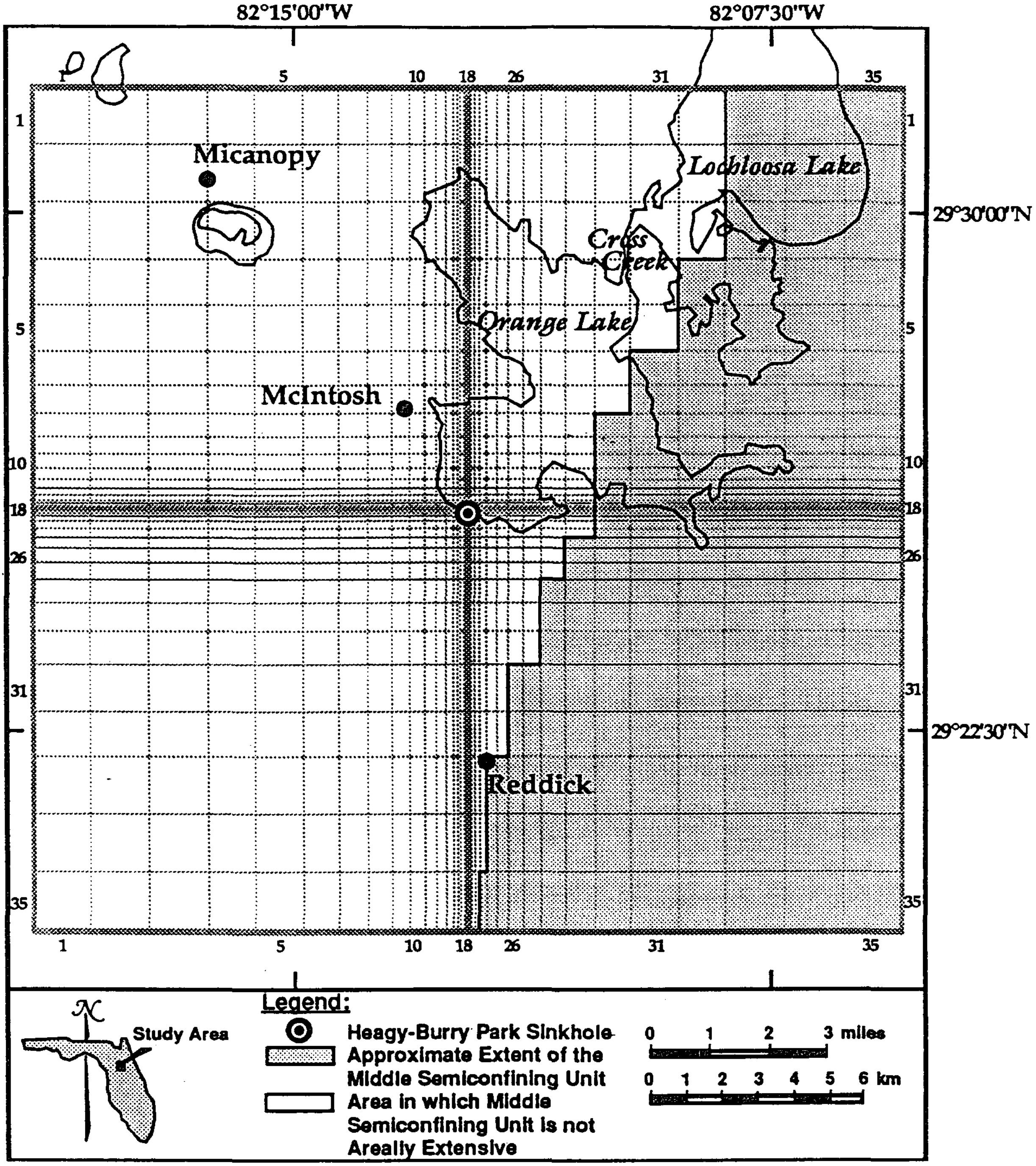


Figure 4-4. Occurrence of the middle semiconfining unit in the model area

4.2.4 Lake and Sinkhole Parameters

The RIV and BCF2 packages in MODFLOW were used to represent the discharge of water from Orange and Lochloosa lakes to the Upper Floridan aquifer through lake bed sediments, the surficial aquifer, and the upper confining unit. In the RIV package, Orange Lake was represented by 394 cells and Lochloosa Lake by 17 cells (see Figure 4-5). The stages for May 1991 for Orange and Lochloosa Lakes was assigned values of 53.97 ft, NGVD, and 55.44 ft, NGVD, respectively, based on model simulations by Robison et al. (1993). Starting values for lake bed conductance were based on the hydraulic conductivity for muck and silt (Anderson and Woessner 1992), a thickness of the muck of approximately 12 feet based on Hardianto (1994), and the areas of the cells that represented the lakes. The final values for lake bed conductance were determined as calibration parameters in the model. Lake bottom elevations were assigned based on bathymetric maps provided by SJRWMD (Wattles 1990). The three cells that represent the sinkholes in Orange Lake were assigned a bottom elevation of 30 ft, NGVD.

In the BCF2 package, the hydraulic connection between layer one and the underlying Upper Floridan aquifer (layer two in the model) at the sinkholes in Orange Lake was simulated by assigning relatively high values of vertical leakance to the three cells that represent the confining unit between layers one and two at the sinkholes. Starting values for vertical leakance at the sinkholes were based on the hydraulic conductivity for cavernous carbonate rocks (Anderson and Woessner 1992) and a thickness of the muck or peat of 3 feet, based on Wilson and Spechler (1992). The final values for vertical leakance (V_{cont1}) at the sinkholes were determined as calibration parameters.

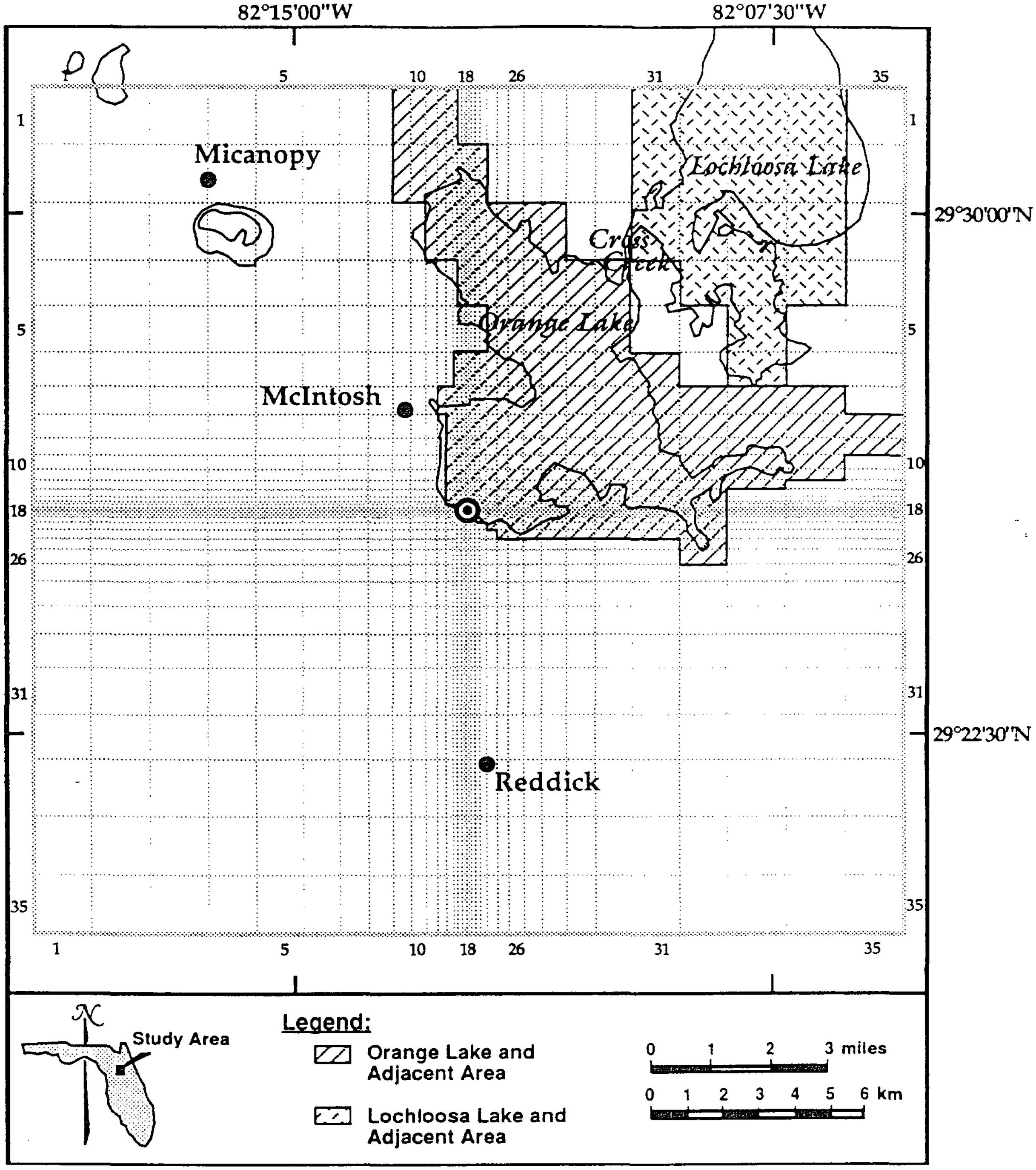


Figure 4-5. Model cells in RIV package representing Orange and Lochloosa lakes

4.2.5 Recharge and Evapotranspiration

Direct recharge generally occurs to the uppermost hydrologic unit. In this simulation, recharge was applied to layer one where the cells are active and to layer two in the area where layer two is unconfined. Option three of the RCH package, which applies recharge to the uppermost active cell in a vertical column, was used. No recharge was applied to the cells in layer one that are active and beneath Orange and Lochloosa lakes. Also, no recharge was applied to the constant head cells in layer one.

Three different recharge rates representing net recharge to the water table and to the ground water system were used in the simulation. Ratios for the percent of rainfall that was net recharge were developed based on soil maps for Alachua and Marion counties (Soil Conservation Service 1978 and 1985) and Stewart (1980). These ratios were 4 percent for the northwestern part of the model area, 29 percent for the southwestern and central parts of the area, and 40 percent for the area in the south where most of the sinkholes are located (see Figure 4-6). For May 1991, the rainfall was 3.99 inches/month, and the net recharge in these areas was, respectively, 4.4×10^{-4} ft/day, 3.2×10^{-3} ft/day, and 4.4×10^{-3} ft/day. The rainfall was based on data collected by SJRWMD at one station within the study area at latitude 29° 31' 10" N and longitude 82° 17' 43" W.

Evapotranspiration generally occurs from the uppermost hydrologic unit. In the model, evapotranspiration occurs from only the active cells in layer one that are not covered by Orange and Lochloosa lakes. For the unconfined part of the aquifer in layer two, even in the area where it has a water table, no evapotranspiration was assigned because all the area is covered by the

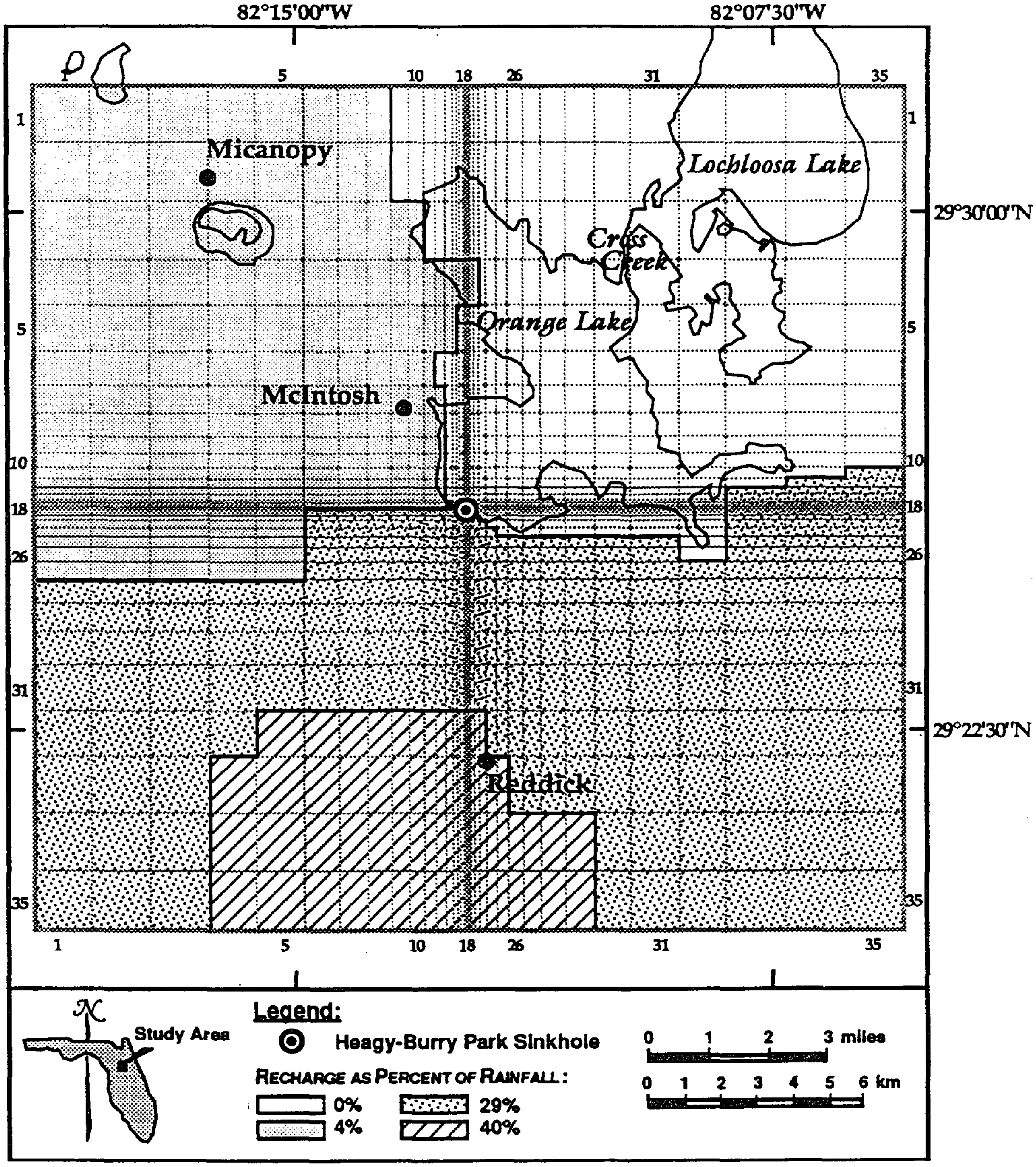


Figure 4-6. Net recharge as a percent of rainfall

Hawthorn Group and the water table is relatively deep below land surface. The maximum evapotranspiration rate from the active cells in layer one was assigned a value of 8.45×10^{-3} ft/day (37 inches/year), based on Bush and Johnston (1988). The surface in layer one at which evapotranspiration is at a maximum is an array whose values were set equal to the elevation of the top of the Hawthorn Group, based on USGS topographic maps of the area. The extinction depth, or the depth below which evapotranspiration ceases, was assumed to be 10 ft.

4.2.6 Pumping Wells

Pumping in the study area was represented by 21 wells in layer two. The pumping rates and locations were based on Motz et al. (1995).

4.2.7 General Head Boundary Conditions

In MODFLOW, at a general head boundary, flow into or out of an active cell from an external source is proportional to the difference between the head in the cell and the head assigned to the external source. The external cell can be considered to represent a constant head boundary located some distance away from the active cell, and flow occurs to or from the cell if the heads in the cell and at the external source are different. If the heads in the cell and at the external source are the same, then flow does not occur between the cell and the external source, and a no-flow boundary, or stream line, can be considered to exist between the active cell and the external source. In the study area, the Floridan aquifer system is a regionally extensive aquifer that does not have physical boundaries or limits that result in constant-head or no-flow boundaries. Thus, in this simulation, it was more realistic to allow for the impact of plugging the sinkhole at the Heagy-Burry Park to extend beyond the boundaries represented in the model.

In the simulation, 140 general head boundaries were assigned around the peripheries of each of layers two and three for a total of 280 general head boundaries. Conductances for each general head boundary were obtained from the product of the transmissivity and the width of the cell divided by the length of the flow path between the constant-head source and the adjacent active cell. The distances from the constant-head sources to the centers of the adjacent active cells are 15,000 ft around all the boundaries of the model. For the May 1991 simulation, values for the boundary head at each external node in layer two were obtained from the potentiometric surface map for May 1991 for the Upper Floridan aquifer. Values for the boundary head at each external node in layer three were assumed equal to the head at each overlying node in layer two because data for the heads in layer three are not available.

4.3 CALIBRATION

4.3.1 Comparison with May 1991 Potentiometric Surface

The ground water flow model was calibrated by calculating the potentiometric surface for layer two (see Figure 4-7) and comparing it to the May 1991 observed potentiometric surface in the Upper Floridan aquifer (Figure 3-3) and also by checking the intersection of the water table in the Hawthorn Group with the water table in the Upper Floridan aquifer in layer one. The area between the two intersections is the area (as noted in Chapter 3) in which the re-wetting capability

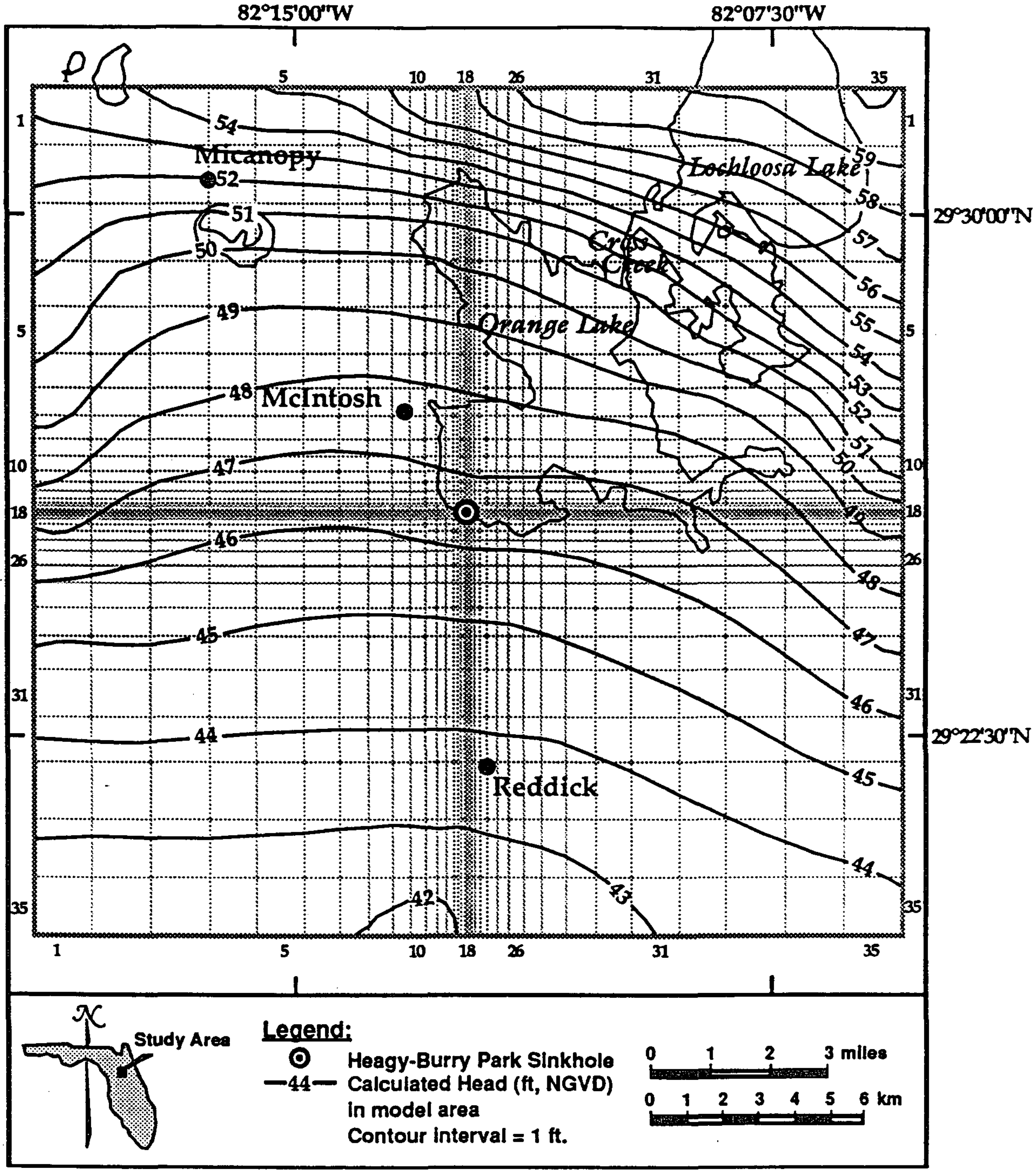


Figure 4-7. Calculated potentiometric surface in the Upper Floridan aquifer (layer two) for May 1991

of the BCF2 package was active (see Figure 4-8). The convergence criterion for the head was set equal to 0.01 ft. During the calibration, values for transmissivity in layer two (T_2), vertical leakance in layer one (V_{contl}), conductances of the lake bed sediments in the RIV package, and the conductances for the general head boundaries in layer two were adjusted until the calculated and observed heads in layer two were within reasonable agreement.

The values of leakance for layer one (V_{contl}) range from 1.5×10^{-3} day^{-1} to 4.5×10^{-3} day^{-1} in the semiconfined area of the Upper Floridan aquifer and up to 7.5×10^{-4} day^{-1} in the other areas of the model (see Figure 4-9). Values of the transmissivity in layer two range from 100,000 ft^2/day in the northeastern part of the model, where the Upper Floridan aquifer is confined, to 6,000,000 ft^2/day in the south-central part of the model area, where the Upper Floridan aquifer is unconfined and receives maximum recharge (see Figure 4-10). These values are related to and consistent with the degree of confinement of the Upper Floridan aquifer (Johnston and Bush 1988). The large values of transmissivities in the southern part of the model area are consistent with even larger values of transmissivity calculated by Faulkner (1973) in the Silver Springs drainage area. In that area, which is just beyond the southern boundary of the model area, values of transmissivities reach 25,000,000 ft^2/day. The conductances for general head boundaries were changed as necessary, consistent with the changing of the transmissivities in the model area.

The values of conductance for the three cells in the RIV package that represent the lake bed sediments at the sinkholes in Orange Lake range from 400,000 to 800,000 ft^2/day. The vertical leakance (V_{contl}) for these cells in the BCF2 package, which represents the confining unit between layers one and two at the sinkholes, ranges from 12 to 30 day^{-1}. These values were

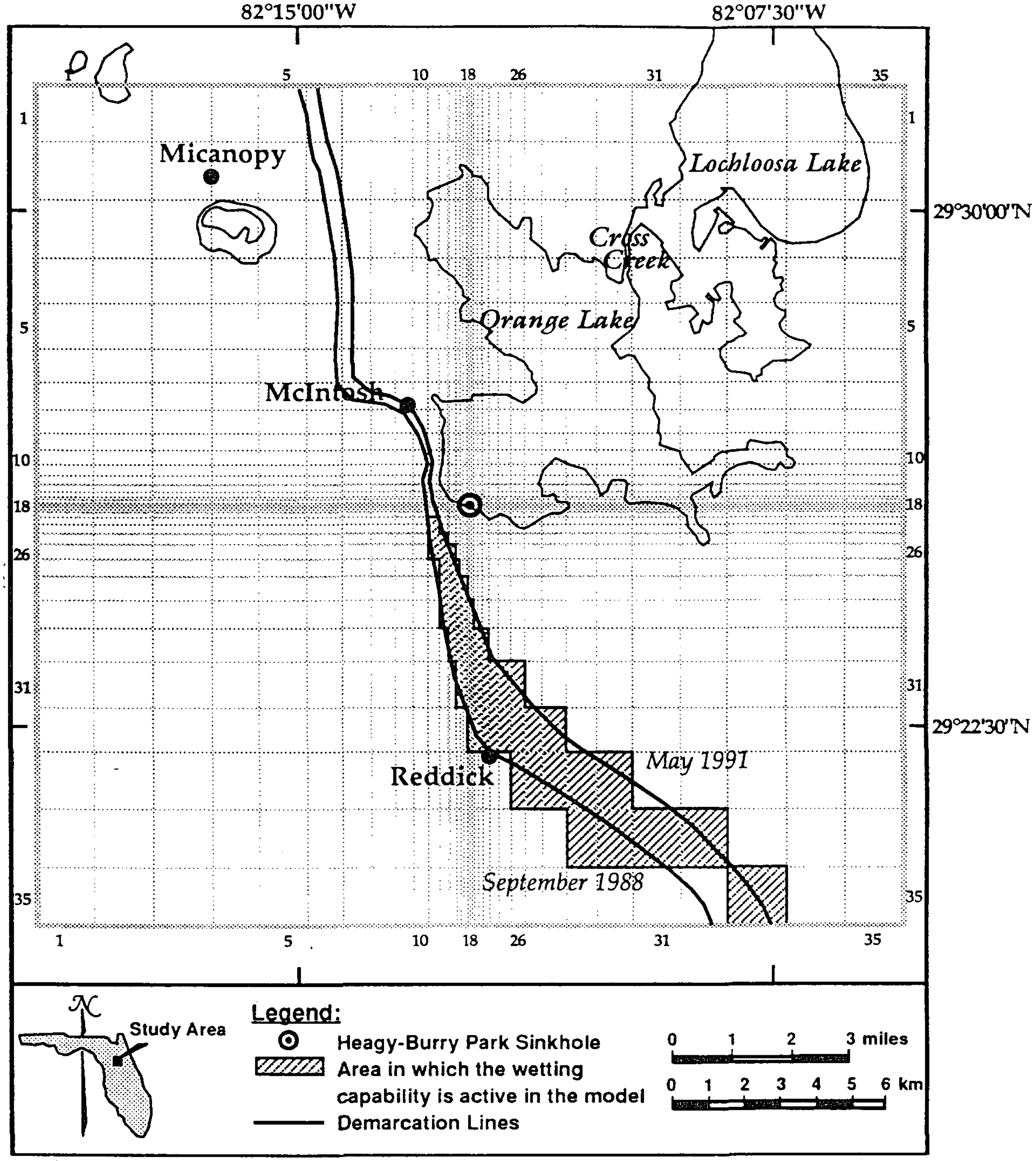


Figure 4-8. Intersection between the potentiometric surface in the Upper Floridan aquifer and the top of the Ocala Limestone in May 1991 and September 1988

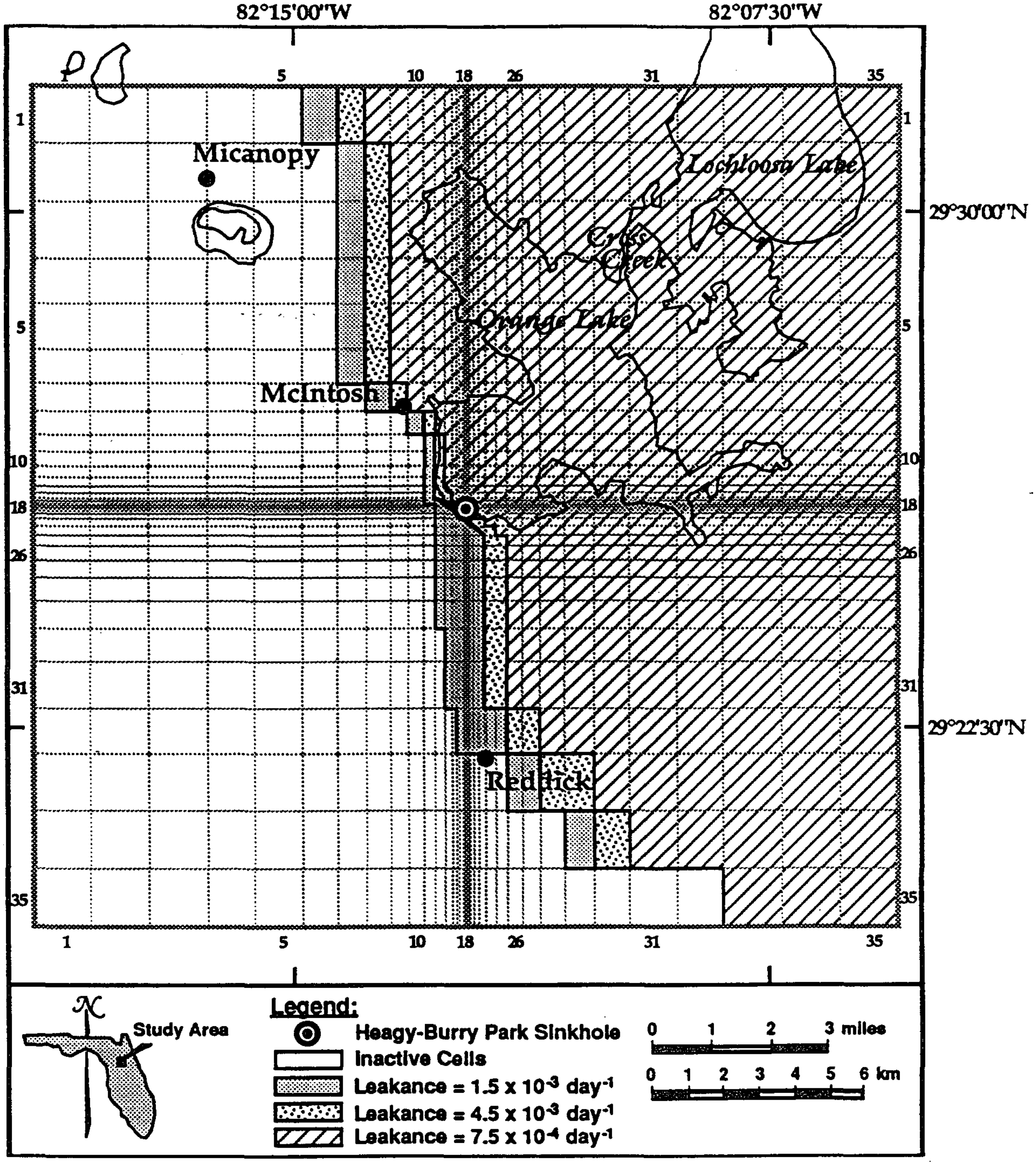


Figure 4-9. Leakance values for the upper confining unit in the May 1991 simulation

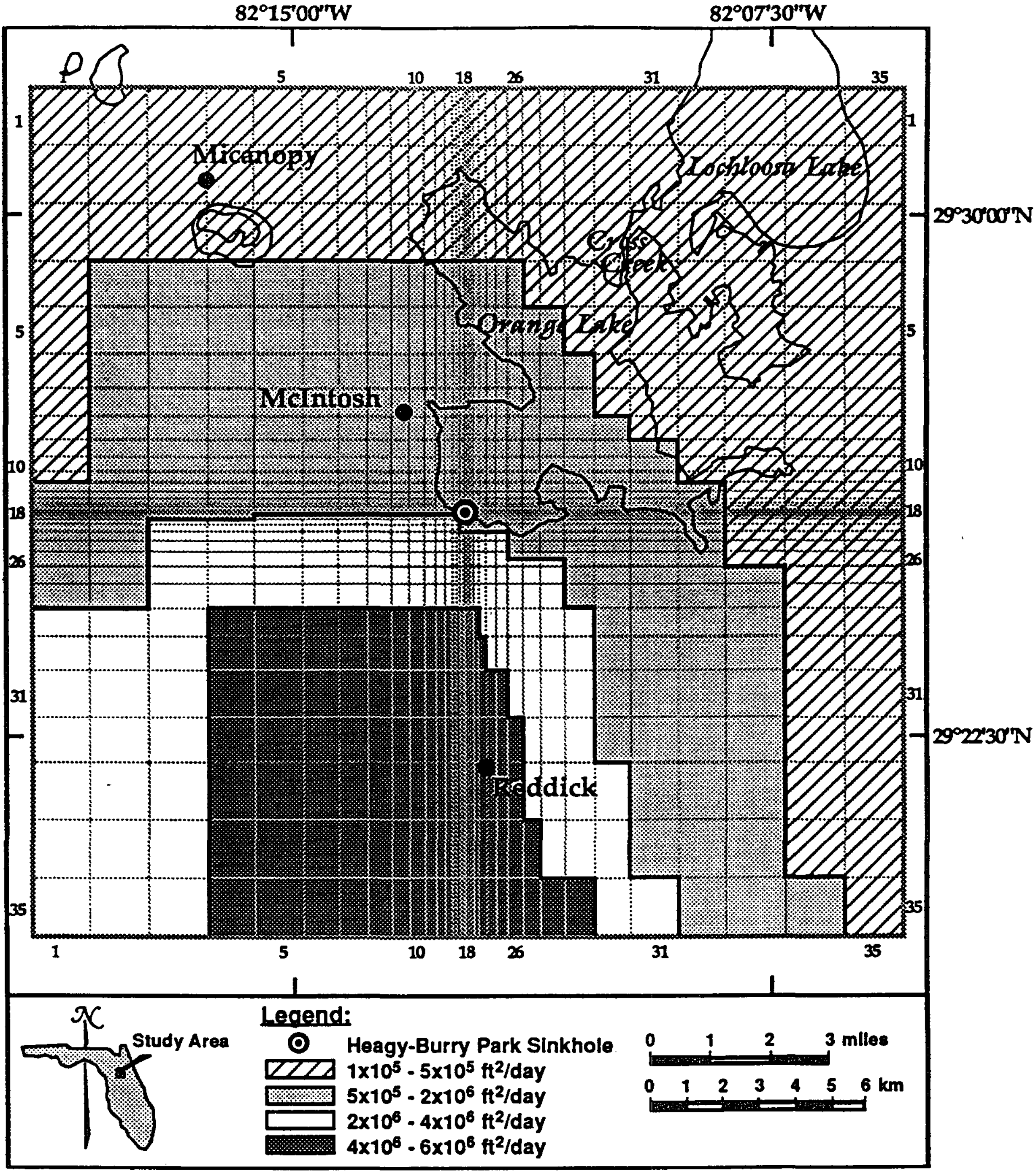


Figure 4-10. Transmissivity values in the Upper Floridan aquifer (layer two) in the May 1991 simulation

obtained by adjusting the conductances and vertical leakances during calibration until the total discharge from the sinkholes in Orange Lake was 36 cfs. This value for May 1991 was determined based on measurements done by Haller and Hoyer (1992) in November 1992. Proportional adjustments from November 1992 to May 1991 were made based on Upper Floridan aquifer loss curves for Orange Lake developed by Robison et al. (1993), which predict smaller values than the measurements made by Haller and Hoyer (1992)(see Table 4-2). It was assumed that the discharge from the sinkhole complex at Heagy-Burry Park is 90 percent of the total leakage from Orange and Lochloosa lakes. The calibrated values for conductance of the lake bed sediments for the rest of the Orange Lake, including Lochloosa Lake, are equal to an assigned value of 1.7×10^{-4} day^{-1} for the leakance multiplied by the area of each cell.

Table 4-2. Orange Lake and sinkhole-complex discharge

	Haller and Hoyer Measurement (1992)		Orange Lake Loss Curves (Robison et al. 1993)		MODFLOW Simulation	
	Sinkhole (cfs)	Orange Lake	Sinkhole	Orange Lake (cfs)	Sinkhole (cfs)	Orange and Lochloosa lakes (cfs)
November 1992	37.6	-----	-----	32.5	-----	-----
May 1991	-----	-----	-----	31.5	36	40

In the model simulation that was considered to be calibrated, the mean of the differences between calculated and observed heads is 0.066 ft, and the standard deviation of the differences is 0.448 ft (see Table 4-3). The maximum head difference is 1.24 ft, which occurs at the cell where the main sinkhole is located, and the minimum head difference is -1.51 ft, which occurs at row 3,

Table 4-3. Statistical results for calibration run and sensitivity analysis for layer two in the May 1991 simulation

Statistical Parameter	Calibration Results	$0.5K_1$	$2.0K_1$	$0.1v_{cont1}$	$10.0V_{cont1}$	$0.5T_2$	$2.0T_2$	$0.1V_{cont2}$	$10.0V_{cont2}$	$0.5T_2$	$2.0T_2$	Q_{totl} 0.5	Q_{total} 2.0
Maximum Head Difference (ft)	1.24 at (18,18)[a]	1.24 at (18,18)	1.24 at (18,18)	1.11 at (18,18)	8.90 at (1,28)	2.94 at (1,28)	0.47 at (28,3)	1.14 at (18,18)	1.30 at (18,18)	1.90 at (1,29)	1.42 at (18,18)	1.25 at (18,18)	1.23 at (18,18)
Minimum Head Difference (ft)	-1.51 at (3,29)	-1.51 at (3,29)	-1.51 at (3,29)	-2.37 at (6,34)	-0.79 at (1.1)	-0.93 at (35,11)	-3.39 at (3,29)	-2.19 at (3,29)	-1.40 at (7,34)	-1.65 at (3,29)	-1.62 at (3,29)	-1.50 at (3,29)	-1.53 at (3,29)
Mean of the Differences (ft)	0.066	0.066	0.066	-0.17	0.9	0.94	-0.64	-0.085	0.113	-0.019	0.157	0.078	0.048
Standard Deviation of the Differences (ft)	0.448	0.448	0.448	0.59	0.893	0.579	0.79	0.52	0.43	0.47	0.516	0.442	0.45
Mean of the Absolute Values (ft)	0.368	0.368	0.368	0.443	0.92	0.988	0.71	0.399	0.371	0.36	0.463	0.366	0.369

[a] Indicates row and column location.

column 29. The maximum head difference of 1.24 ft at the sinkhole is acceptable because the observed potentiometric map cannot reproduce the heads in that small an area with complete accuracy. The minimum head difference of -1.51 ft is in an area where the equipotentional lines are closely spaced and thus the heads change over a short distance, making it difficult to obtain an exact calibration in that area. In all the other areas of the model, the difference between the calculated and observed heads in layer two is less than 1 foot.

4.3.2 Water Budget

In the May 1991 simulation, inflows to the ground water system are derived from constant head boundaries, direct recharge to layers one and two, discharge from the lakes, and head dependent boundaries (see Table 4-4). Outflows from the ground water system occur by means of wells, evapotranspiration from layer one, discharge to the lakes, and head dependent boundaries. Evapotranspiration outflow is very small because it occurs only from the cells that are adjacent to

Table 4-4. Water budget for the ground water system for the May 1991 simulation

Type of Boundary	Inflow (ft^3/day)	Outflow (ft^3/day)
Constant Head	2.58×10^6	---
Pumping Wells	---	3.41×10^5
Areal Recharge	9.40×10^6	---
Evapotranspiration	---	6.25×10^4
Lake	3.51×10^6	7.30×10^4
Head Dependent	2.02×10^7	3.50×10^7
Total	3.56×10^7	3.55×10^7

the lakes. Away from the lakes, the water table in Hawthorn Group declines to depths below land surface greater than the assumed extinction depth of 10 ft, and thus evapotranspiration is minimal. The discharge to the lakes also is small, because this occurs only in the northern part of the lakes where the potentiometric surface of layer one is higher than the lake stage.

The net discharge from Orange and Lochloosa lakes, which is the sum of the discharge from Orange and Lochloosa lakes to the Upper Floridan aquifer minus a relatively small component of flow from the ground water system into the lakes, is 3.43×10^6 ft^3/day. As noted in section 4.3.1, approximately 90 percent of the discharge from the lakes occurs at the sinkhole complex in Orange Lake. The discharge is 1.435×10^6 ft^3/day at the main sinkhole and 0.836×10^6 ft^3/day at each of the other two sinkholes.

4.4 SENSITIVITY ANALYSIS

A sensitivity analysis was performed on the calculated heads in layer two and also on the calculated water table in layer one. Based on the head calculated for layer one, it was observed that the heads in the area where the water table declines are very sensitive to the changes in vertical leakance values for layer one. The heads in layer two were very sensitive to changes in the transmissivities and conductances, especially for the southern part but less sensitive compared to changes in vertical leakance for layer one (see Table 4-3). The heads in layer three were less sensitive to changes in the transmissivity and conductances in layer two. Also, because of the relatively large transmissivities in layer two, the heads in layer two were not sensitive to changes in the pumping rate.

4.5 VERIFICATION OF THE MODEL

The model calibrated for the May 1991 potentiometric surface, which was the lowest potentiometric surface during 1985-1991, was verified by running it for September 1988 conditions, which represented the highest potentiometric surface during the same period. In the verification of the model, the heads at the general head boundaries were changed based on the observed potentiometric surface for September 1988. Also the recharge rate was changed based on rainfall for September 1988. For September 1988, the rainfall was 11.00 inches/month, and the net recharge was assigned, respectively, 1.2×10^{-3} ft/day, 8.7×10^{-3} ft/day, and 1.2×10^{-2} ft/day, based on the percent of rainfall that becomes net recharge (Figure 4-4). The lake stages were changed based on simulations for September 1988 by Robison et al. (1993), and they were assigned values of 57.72 ft, NGVD, for Orange Lake and 58.16 ft, NGVD, for Lochloosa Lake. The pumping rates for the wells in layer two were adjusted for September water use based on Marella (1988). All of the other hydrologic parameters in the model were the same.

The calculated potentiometric surface for September 1988 (Figure 4-11) was then compared with the observed potentiometric surface for September 1988 (Figure 3-2). The mean of the differences is -0.36 ft, and the standard deviation of the differences is 0.44 feet. The maximum head difference is 1.19 feet, which occurs at row 1, column 10, and the minimum head difference is -2.52 ft, which occurs at row 1, column 35 ft. Compared to the calibrated model for May 1991, these values are slightly greater but still well within an acceptable range. The maximum and the minimum differences occur at the northern boundary of the model, far from the area where the sinkholes are located.

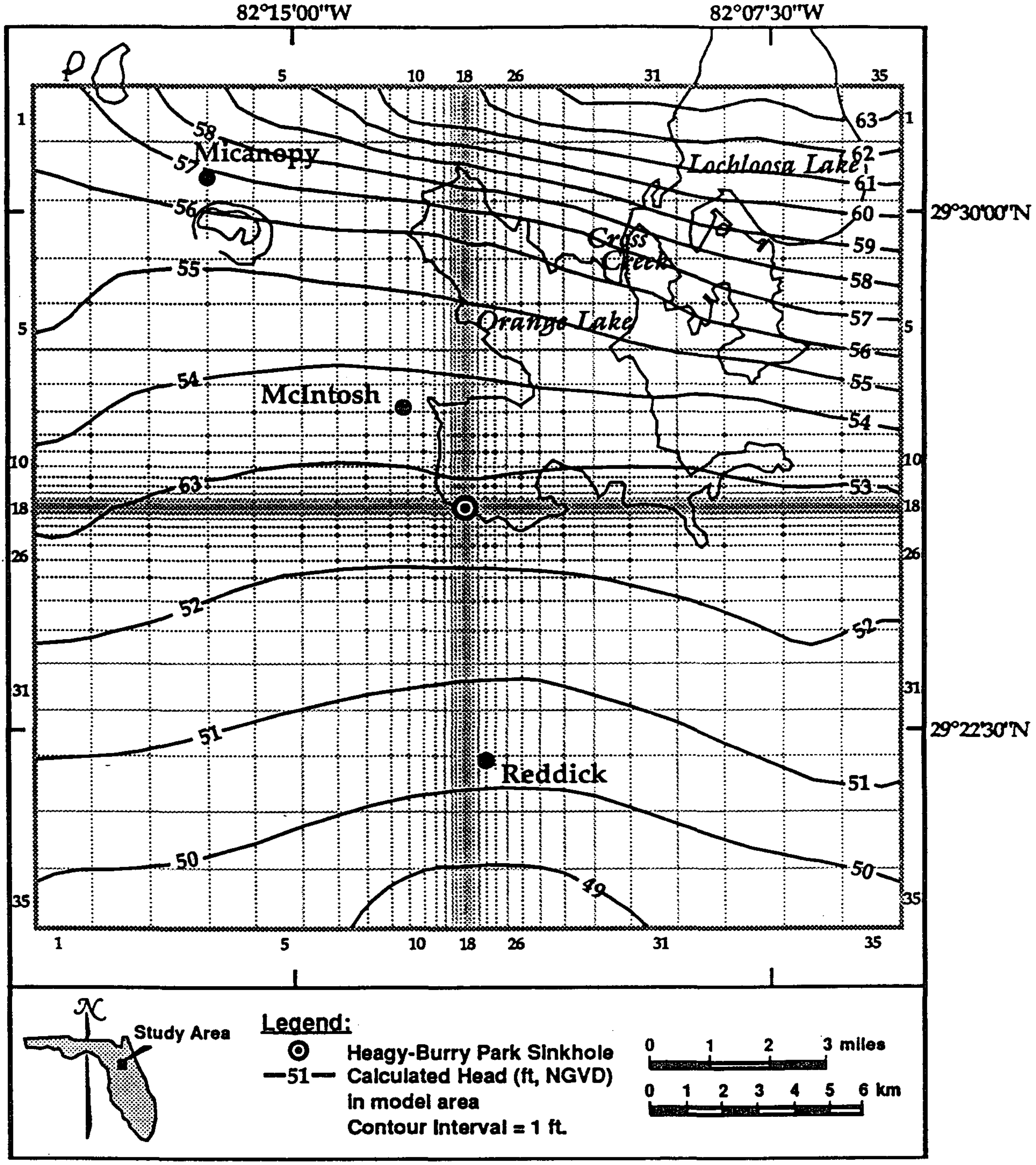


Figure 4-11. Calculated potentiometric surface in the Upper Floridan aquifer (layer two) for September 1988

The discharge of the sinkholes for September 1988 (24.2 cfs) is approximately 30 percent less than the discharge of the sinkholes for May 1991, even though the Orange Lake stage for September 1988 was higher than for May 1991. This happens because the driving force for the sinkhole discharge, i.e., the difference between the lake stage and the potentiometric surface, is smaller for September 1988 than it is for May 1991.

In the September 1988 simulation, inflows to and outflows from the ground water model are derived in the same way as for May 1991 (see Table 4-5). The net discharge from Orange and Lochloosa lakes to the ground water system is 2.29×10^6 ft^3/day. The discharge is 0.965×10^6 ft^3/day at the main sinkhole and 0.563×10^6 ft^3/day at each of the other two sinkholes.

Table 4-5. Water budget for the ground water system for the September 1988 simulation

Type of Boundary	Inflow (ft^3/day)	Outflow (ft^3/day)
Constant Head	1.44×10^6	1.97×10^3
Pumping Wells	---	2.12×10^5
Areal Recharge	2.56×10^7	---
Evapotranspiration	---	1.75×10^6
Lake	2.42×10^6	1.27×10^5
Head Dependent	1.32×10^7	4.06×10^7
Total	4.26×10^7	4.27×10^7

4.6 TRANSIENT SIMULATION

4.6.1 Period of Simulation

A 23-month period from November 1, 1989, to September 30, 1991, was selected for a transient simulation. This period of time was chosen in order to simulate different scenarios (described in Chapter 5), and it is also based on the results of the hydrologic model SSARR for Orange and Lochloosa lakes done by SJRWMD (Robison et al. 1993). The ground water model was run for steady state for November 1989, and the heads calculated by the model were used as starting heads for the transient simulation. The May 1991 low potentiometric surface, the time period for which the model was calibrated, is included in the transient simulation period. The transient simulation was divided into 23 stress periods (equal to the number of months) because the pumping rates, lake stages, boundary heads, and net recharge all changed each month.

4.6.2 MODFLOW Files

The MODFLOW input files for the May 1991 simulation were modified to include the parameters that were changed during the transient simulation. The net recharge rate was changed based on monthly rainfall data from November 1989 to September 1991 (see Figure 4-12). The areal distribution of net recharge (Figure 4-5) remained the same. Also, the pumping rates of the wells in layer two were changed for each month based on Marella (1988). The stages at Orange and Lochloosa lakes also were changed based on monthly simulations by Robison et al. (1993). The evapotranspiration rate remained the same during the transient simulation. The heads at the

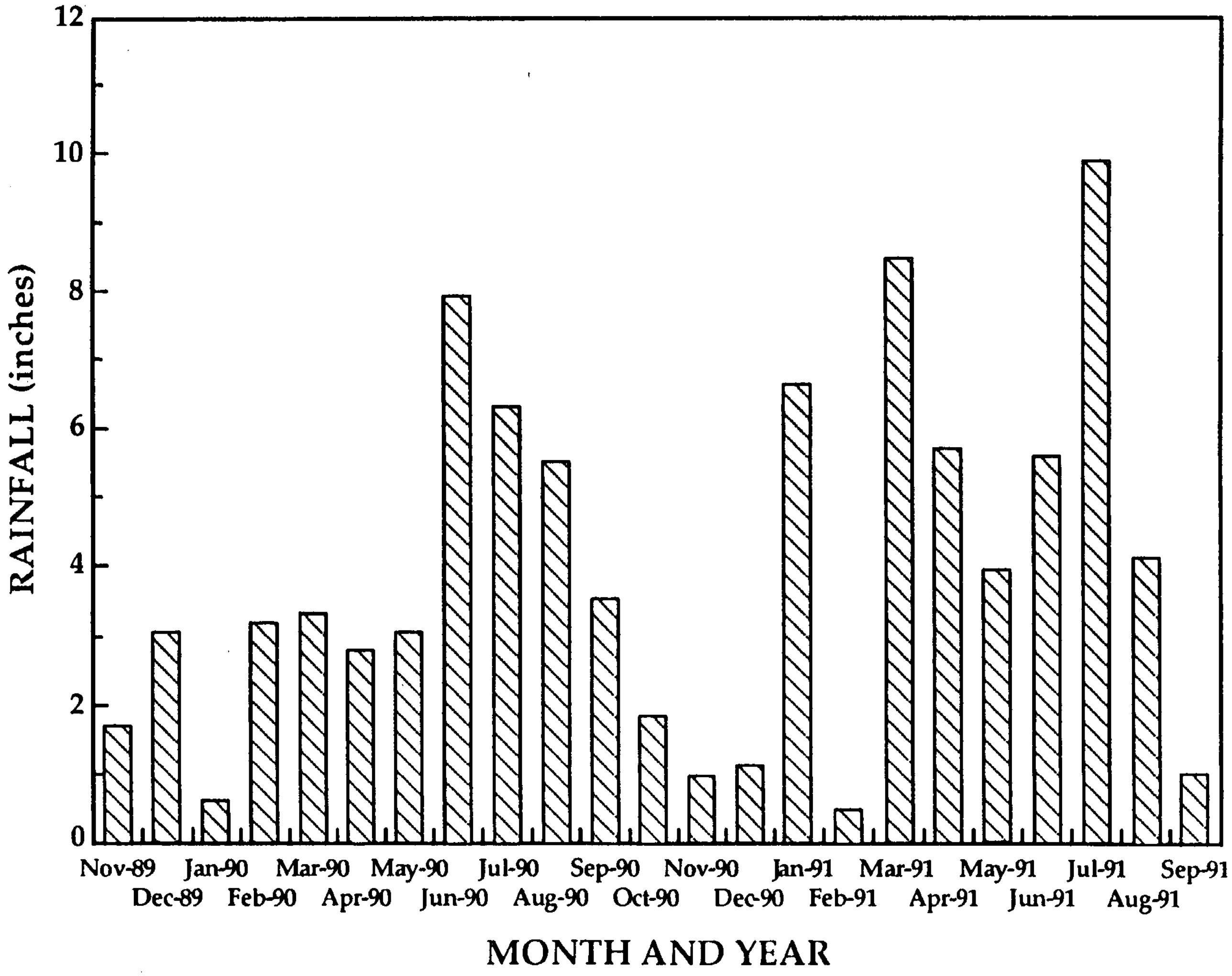


Figure 4-12. Rainfall from November 1989 to September 1991

general head boundaries were changed every month based on interpolation between May and September potentiometric maps.

All of the hydrogeological parameters resulting from the May 1991 steady-state calibration were used in the transient simulation except for the storage coefficients, which were modified for the transient condition. An unconfined aquifer storage coefficient of 0.1 was assigned to the active cells in layer one, based on Tibbals (1990). For layer two, as a confined/unconfined layer, two storage coefficients were assigned. The first was a primary storage coefficient of 0.001, based on Anderson and Woessner (1992), and the second was a secondary storage coefficient of 0.3, also based on Anderson and Woessner (1992). Layer three is a confined layer in the model, so only one primary storage coefficient of 0.001 was assigned.

4.6.3 Results of Simulation

In order to evaluate the transient simulation, the heads calculated from the model were compared with observed heads measured in one well at Cross Creek, which is located between cells at row 3, column 30; row 3, column 31; row 4, column 30; and row 4, column 31 of the model at latitude 29° 29' 09" N and longitude 82° 09' 51" W. There were also two other monitoring wells in the area, but for one the data were available only from 1992, and the other well was very close to the boundary of the model.

The head from the transient simulation that was used for comparison was calculated as an average of the head in the four cells adjacent to the monitoring well. The results show that there is a very small difference of 0.07 feet for May 1990, 0.46 feet for September 1990, and 0.85 feet for May 1991 (see Figure 4-13). For September 1991, there is no information, but the hydrograph of the well at Cross Creek and the calculated head both show the same upward trend.

During the transient simulation, the total inflow to and outflow from the ground water system averaged about 3.91×10^7 ft^3/day (see Table 4-6). The net discharge (inflow-outflow) from Orange and Lochloosa lakes to the ground water system is 3.28×10^6 ft^3/day. The discharge from the sinkhole complex in Orange Lake is about 90 percent of this value, or about 34.2 cfs.

Table 4-6. Water budget for the ground water system for the November 1989 - September 1991 simulation

Type of Boundary	Inflow (ft^3/day)	Outflow (ft^3/day)
Storage	3.71×10^6	3.56×10^6
Constant Head	2.39×10^6	-
Pumping Wells	-	2.79×10^6
Areal Recharge	9.34×10^6	-
Evapotranspiration	-	1.25×10^5
Lake	3.38×10^6	9.69×10^4
Head Dependent	2.02×10^7	3.50×10^7
Total	3.90×10^7	3.91×10^7

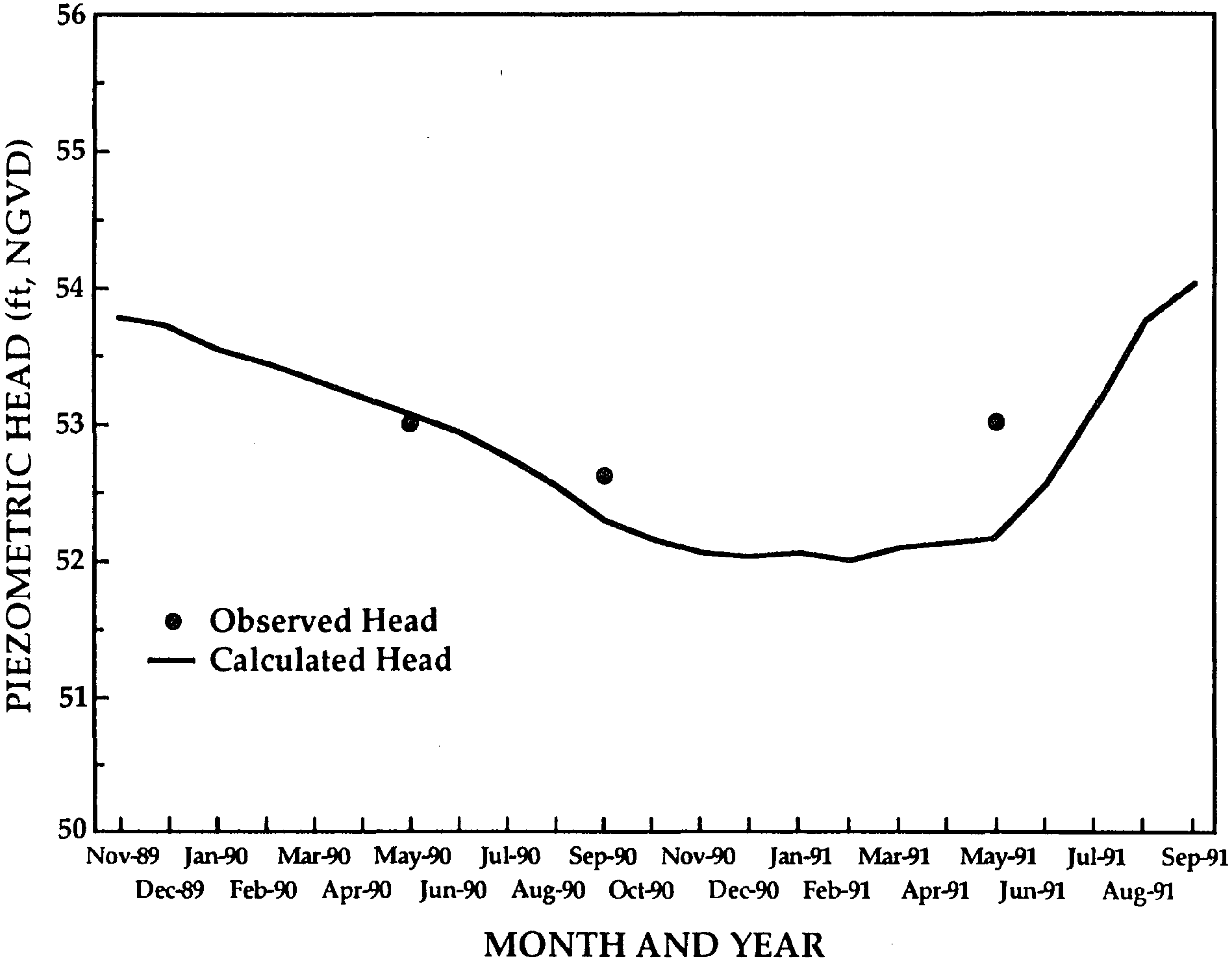


Figure 4-13. Calculated and observed heads during transient simulation

5.0 IMPACT ANALYSIS

5.1 SINKHOLE-COMPLEX DISCHARGE-CONTROL SCENARIOS

The impacts of controlling the sinkhole-complex discharge were evaluated by modeling the changes in ground water levels in the Upper Floridan aquifer that would result from three hypothetical sinkhole-complex discharge-control scenarios (see Table 5-1). The first scenario

Table 5-1. Sinkhole-complex discharge-control scenarios

Scenario	Description
1a and 1b	Complete cessation of sinkhole-complex discharge by plugging or using a dam to separate the sinkhole complex from the rest of the lake.
2a, 2b, and 2c	Passive partial control of the sinkhole-complex discharge using a fixed crest weir to separate the sinkhole complex from the rest of the lake at crest elevations of 56, 55, and 54 ft, NGVD.
3a, 3b, and 3c	Active control of the sinkhole-complex discharge using a gated structure (with bottom discharge) to separate the sinkhole complex from the rest of the lake under the following control scenarios: gates kept open (allowing discharge to the sinkhole complex) until lake level drops to 56 ft, NGVD, and then gates are kept closed until lake level rises above 58 ft, NGVD; gates kept open (allowing discharge to the sinkhole complex) until lake level drops to 55 ft, NGVD, and then gates are kept closed until lake rises above 58 ft, NGVD; and gates kept open (allowing discharge to the sinkhole complex) until lake level drops to 54 ft, NGVD, and then gates are kept closed until lake level rises above 58 ft, NGVD.

consisted of completely stopping the sinkhole discharge by plugging the sinkhole or constructing a dam around the sinkhole complex. The second scenario consisted of using a fixed crest weir to achieve passive control of the sinkhole discharge, and the third scenario consisted of simulating the operation of a gated structure to achieve active control of the sinkhole discharge. For scenario one, impacts relative to drought conditions were evaluated relative to the May 1991 potentiometric surface, and impacts relative to a high rainfall period were evaluated relative to the September 1988 potentiometric surface. For scenarios two and three, transient simulations were performed and compared to existing conditions in the period from November 1989 to September 1991, which was a subset of the simulation period used by Robison et al. (1993) for Orange and Lochloosa lakes.

5.2 PLUGGING THE SINKHOLE COMPLEX (SCENARIO ONE)

5.2.1 Plugging the Sinkhole Complex for May 1991

The sinkhole complex was "plugged" in the calibrated model that represents the May 1991 potentiometric surface (low water-level condition) by reducing the conductance values of the lake bed sediments in the cells in the RIV package that represent the sinkhole complex. These values were reduced from 400,000 - 800,000 ft^2/day to 1 - 2 ft^2/day, based on the leakance values and hydrogeologic parameters of the lake bed sediments in the rest of the lake. The ground water model was re-run with the reduced conductance values in the sinkhole complex, and the changes in head in layer two for the simulated May 1991 case that would occur under this scenario were calculated and plotted (see Figure 5-1). The maximum decrease in head (1.54 ft) in the upper

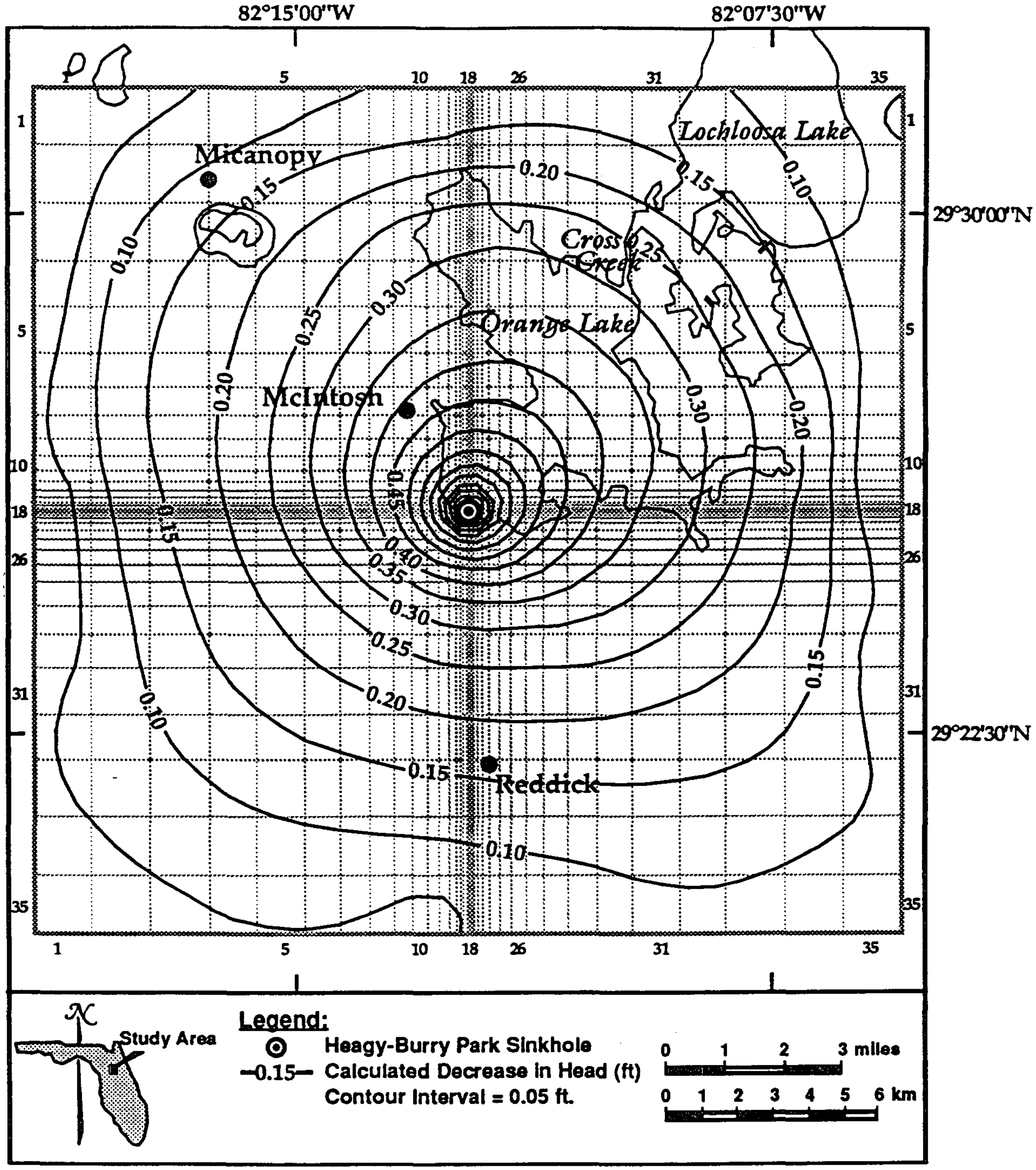


Figure 5-1. Calculated decrease in head in the Upper Floridan aquifer for the May 1991 simulation due to plugging (or damming) the sinkhole complex

Floridan aquifer due to plugging the sinkhole occurs at the main sinkhole. The decrease in head diminishes towards the boundaries of the model, where the head decrease is about 0.05 ft. The net discharge (inflow-outflow) from Orange and Lochloosa lakes to the ground water system in the May 1991 simulation is reduced from 3.43×10^6 ft^3/day (Table 4-4) to 3.45×10^5 ft^3/day when the sinkhole complex is plugged (or dammed) (see Table 5-2).

Table 5-2. Water budget for the ground water system for the May 1991 simulation when the sinkhole complex is plugged (or dammed)

Type of Boundary	Inflow (ft^3/day)	Outflow (ft^3/day)
Constant Head	2.63×10^6	-
Pumping Wells	-	3.41×10^5
Areal Recharge	9.40×10^6	-
Evapotranspiration	-	5.12×10^4
Lake	4.14×10^5	6.93×10^4
Head Dependent	2.12×10^7	3.30×10^7
Total	3.36×10^7	3.35×10^7

5.2.2 Plugging the Sinkhole Complex for September 1988

The sinkhole complex also was "plugged" for the ground water model that represents the September 1988 potentiometric surface (high water-level condition) using the same reduced conductance values for the sinkhole complex area that were used in the revised May 1991 simulation. The ground water model was re-run with the reduced leakance values, and the changes in head in layer two for the simulated September 1988 case were calculated and plotted (see Figure 5-2).

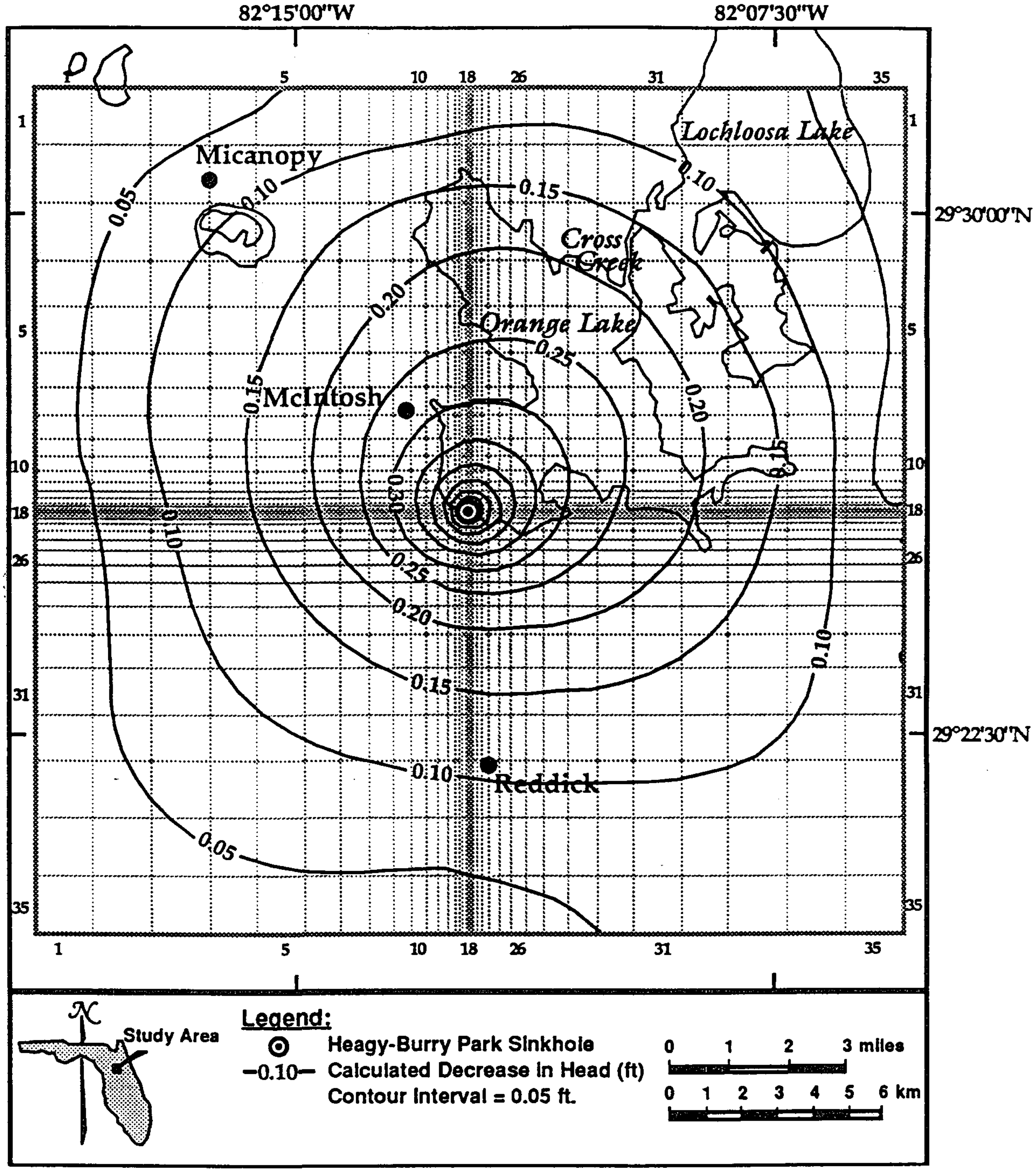


Figure 5-2. Calculated decrease in head in the Upper Floridan aquifer for the September 1988 simulation due to plugging (or damming) the sinkhole complex

The maximum decrease in head (1.03 ft) in the upper Floridan aquifer due to plugging the sinkhole complex occurs at the main sinkhole. Similar to the May 1991 simulation, the decrease in head diminishes to about 0.05 ft at the boundaries of the model. The maximum decrease in head for September 1988 (1.03 ft) is smaller than the decrease in head for May 1991 (1.54 ft) because the potentiometric surface of the Upper Floridan aquifer rises faster than the level of Orange Lake during high water level periods, and the head difference between the lake and the potentiometric surface is generally smaller in September than it is in May. Thus, the head decrease that results from plugging the sinkhole complex is correspondingly smaller for the September 1988 simulation than it is for the May 1991 simulation. The net discharge (inflow-outflow) from Orange and Lochloosa lakes to the ground water system in the September 1991 simulation is reduced from 2.29×10^6 ft^3/day (Table 4-5) to 2.25×10^5 ft^3/day when the sinkhole complex is plugged (or dammed) (see Table 5-3).

Table 5-3. Water budget for the ground water system for the September 1988 simulation when the sinkhole complex is plugged (or dammed)

Type of Boundary	Inflow (ft^3/day)	Outflow (ft^3/day)
Constant Head	1.47×10^6	1.80×10^3
Pumping Wells	-	2.12×10^5
Areal Recharge	2.56×10^7	-
Evapotranspiration	-	1.72×10^6
Lake	3.48×10^5	1.23×10^5
Head Dependent	1.38×10^7	3.92×10^7
Total	4.12×10^7	4.13×10^7

5.3 PASSIVE PARTIAL CONTROL OF THE SINKHOLE-COMPLEX DISCHARGE WITH A FIXED CREST WEIR (SCENARIO TWO)

5.3.1 Weir Crest Elevation at 56 ft, NGVD

The transient simulation model described in Section 4.6 was used to simulate passive control of the sinkhole-complex discharge using a fixed crest weir. All of the hydrogeologic parameters used in the 23 stress periods in the transient simulation were unchanged except for the stages of Orange and Lochloosa lakes. For this simulation, the stage levels for Orange and Lochloosa lakes simulated by Robison et al. (1993) for existing conditions and for conditions that corresponded to scenario two with the weir elevations at 56, 55, and 54 ft, NGVD, were used as input data for the lake levels in the ground water model (see Figure 5-3 and Tables 5-4 and 5-5). In this scenario, it was assumed that a fixed crest weir separating the sinkhole complex from the rest of the lake would be constructed about 300 feet offshore east of the sinkhole complex, based on Hardianto (1994). In the model, this area was represented by the cells in row 17, columns 16, 17, 18, and 19; row 18, columns 17, 18, and 19; row 19, columns 18 and 19, and row 20, column 19. It was assumed that this area would quickly become dry when the level of Orange Lake dropped below 56 ft, NGVD. It was verified that this response was a reasonable assumption by calculating that the water level in the sinkhole complex would drop in a few days if the sinkhole complex were approximated as a large slug injection well extending into the Upper Floridan aquifer, based on Papadopulos et al. (1973). It was assumed that the lake stage in the three cells (row 18, columns 17 and 18; and row 19, column 18) within this area that represented the sinkhole complex would drop to 48.5 ft, NGVD, which was the average of the head in the Upper

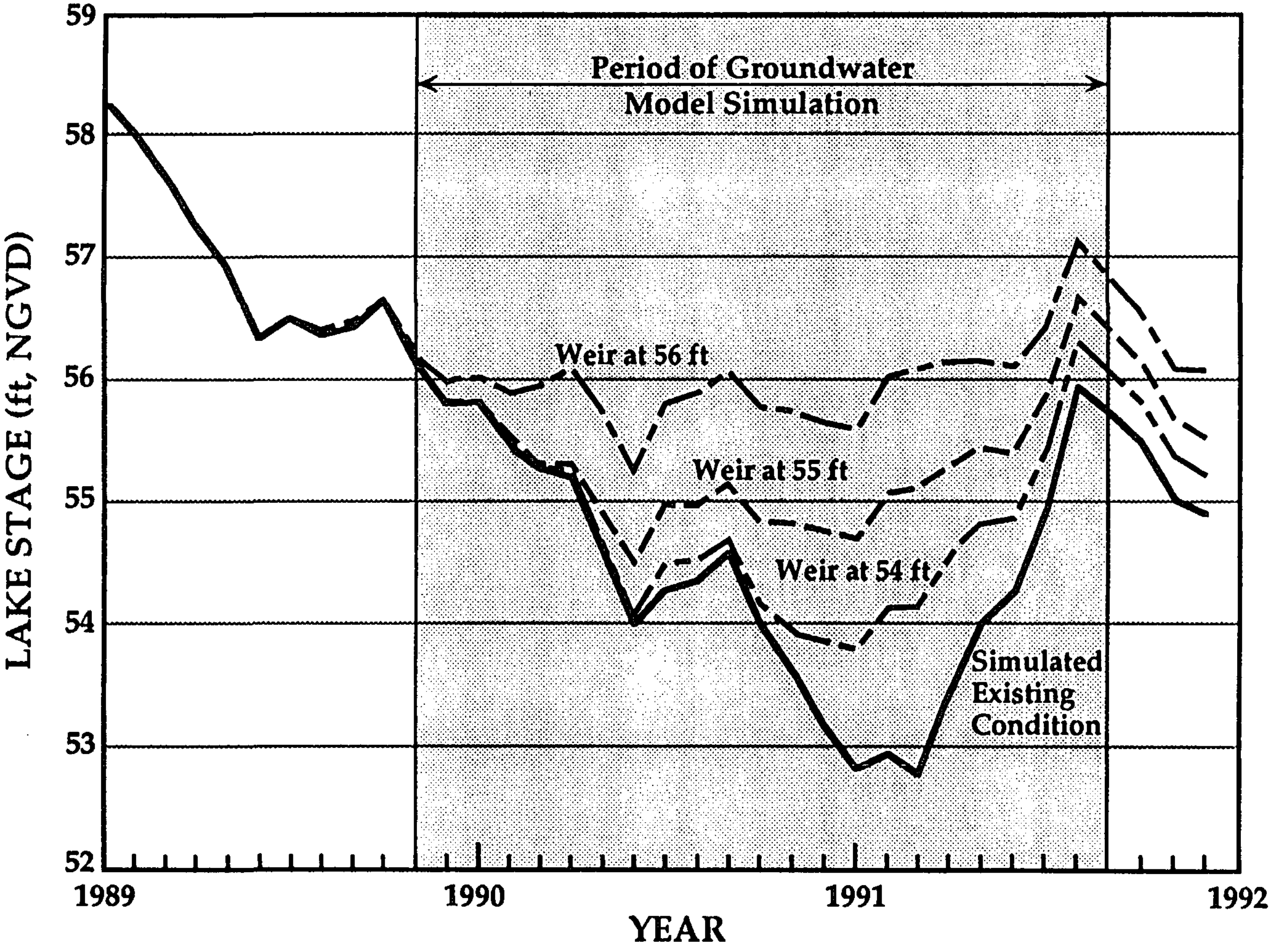


Figure 5-3. Calculated stages at Orange Lake for simulated existing conditions and fixed crest weir scenario (based on Robison et al. 1993)

Table 5-4. Calculated stages for Orange Lake when the sinkhole-complex discharge is controlled by a fixed crest weir

Date	Existing Simulated Conditions (ft, NGVD)	Weir Crest at 56 ft, NGVD (ft, NGVD)	Weir Crest at 55 ft, NGVD (ft, NGVD)	Weir Crest at 54 ft, NGVD (ft, NGVD)
Nov-89	56.13	56.18	56.15	56.14
Dec-89	55.79	55.96	55.81	55.80
Jan-90	55.80	56.01	55.83	55.82
Feb-90	55.44	55.88	55.48	55.47
Mar-90	55.26	55.93	55.31	55.29
Apr-90	55.20	56.08	55.29	55.24
May-90	54.73	55.73	54.88	54.76
Jun-90	54.01	55.24	54.50	54.07
Jul-90	54.29	55.79	54.97	54.49
Aug-90	54.36	55.88	54.97	54.52
Sep-90	54.59	56.07	55.14	54.70
Oct-90	54.03	55.77	54.84	54.17
Nov-90	53.64	55.74	54.83	53.94
Dec-90	53.20	55.65	54.76	53.86
Jan-91	52.85	55.59	54.71	53.81
Feb-91	52.97	56.03	55.08	54.14
Mar-91	52.80	56.10	55.13	54.15
Apr-91	53.48	56.16	55.32	54.60
May-91	54.02	56.16	55.45	54.84
Jun-91	54.28	56.11	55.42	54.88
Jul-91	54.93	56.42	55.85	55.39
Aug-91	55.95	57.16	56.69	56.32
Sep-91	55.74	56.84	56.40	56.08

Source: Based on Robison et al. 1993

Table 5-5. Calculated stages for Lochloosa Lake when the sinkhole-complex discharge is controlled by a fixed crest weir

Date	Existing Simulated Conditions (ft, NGVD)	Weir Crest at 56 ft, NGVD (ft, NGVD)	Weir Crest at 55 ft, NGVD (ft, NGVD)	Weir Crest at 54 ft, NGVD (ft, NGVD)
Nov-89	56.57	56.55	56.53	56.53
Dec-89	56.27	56.27	56.24	56.23
Jan-90	56.28	56.33	56.25	56.24
Feb-90	55.88	56.05	55.85	55.84
Mar-90	55.74	56.09	55.72	55.70
Apr-90	55.66	56.20	55.65	55.62
May-90	55.13	55.82	55.14	55.10
Jun-90	54.53	55.30	54.60	54.51
Jul-90	55.00	55.87	55.14	54.99
Aug-90	54.87	56.00	55.20	54.90
Sep-90	54.99	56.25	55.40	55.03
Oct-90	54.57	55.86	54.98	54.60
Nov-90	54.51	55.80	54.91	54.54
Dec-90	54.38	55.67	54.79	54.41
Jan-91	54.29	55.58	54.70	54.32
Feb-91	54.79	56.14	55.23	54.82
Mar-91	54.93	56.28	55.38	54.95
Apr-91	55.13	56.57	55.76	55.17
May-91	55.46	56.89	56.23	55.64
Jun-91	55.23	56.68	56.00	55.45
Jul-91	55.65	56.86	56.27	55.78
Aug-91	56.40	57.36	56.79	56.42
Sep-91	56.35	57.17	56.67	56.32

Source: Based on Robison et al. 1993

Floridan aquifer at the sinkhole complex for the period of simulation. At the other cells within this area, it was assumed that the lake stage would drop to the elevation of the bottom of the lake. In the monthly stress periods when the level of Orange Lake was above 56 ft, NGVD, it was simulated that there was no weir around the sinkhole complex and that the lake stages at the cells within the enclosed area were the same as the rest of the lake.

The impacts that scenario two with the fixed crest weir set at 56 ft, NGVD, would have on heads in the Upper Floridan aquifer were calculated using the transient simulation model, and the heads were plotted for three locations (see Figure 5-4). The first location (A, at row 18, column 18) is at the main sinkhole, where the impact in terms of head change would be the greatest, and the second location (B, at row 27, column 24) is approximately one mile south of Orange Lake in an area where the Hawthorn Group confining unit is relatively thin and where numerous sinkholes occur. The third location (C, at row 33, column 18) is a relatively distant five miles south of Orange Lake.

Abrupt changes occur at location A with the fixed crest weir at 56 ft, NGVD (see Figure 5-5), as the lake stage falls below and then rises above the crest of the weir, causing the area where the sinkholes are located to go dry and then be re-wetted in a short period of time. When the lake stage is below the crest of the weir, the three hydrographs at A, B, and C for the conditions with and without the weir follow the same trend, but the impacts in terms of head changes diminish with distance away from Orange Lake. Beginning in February 1991, the hydrographs that would result from installation of the weir are slightly higher, particularly at location A, than the hydrographs for the existing conditions because the increased lake stage that is maintained

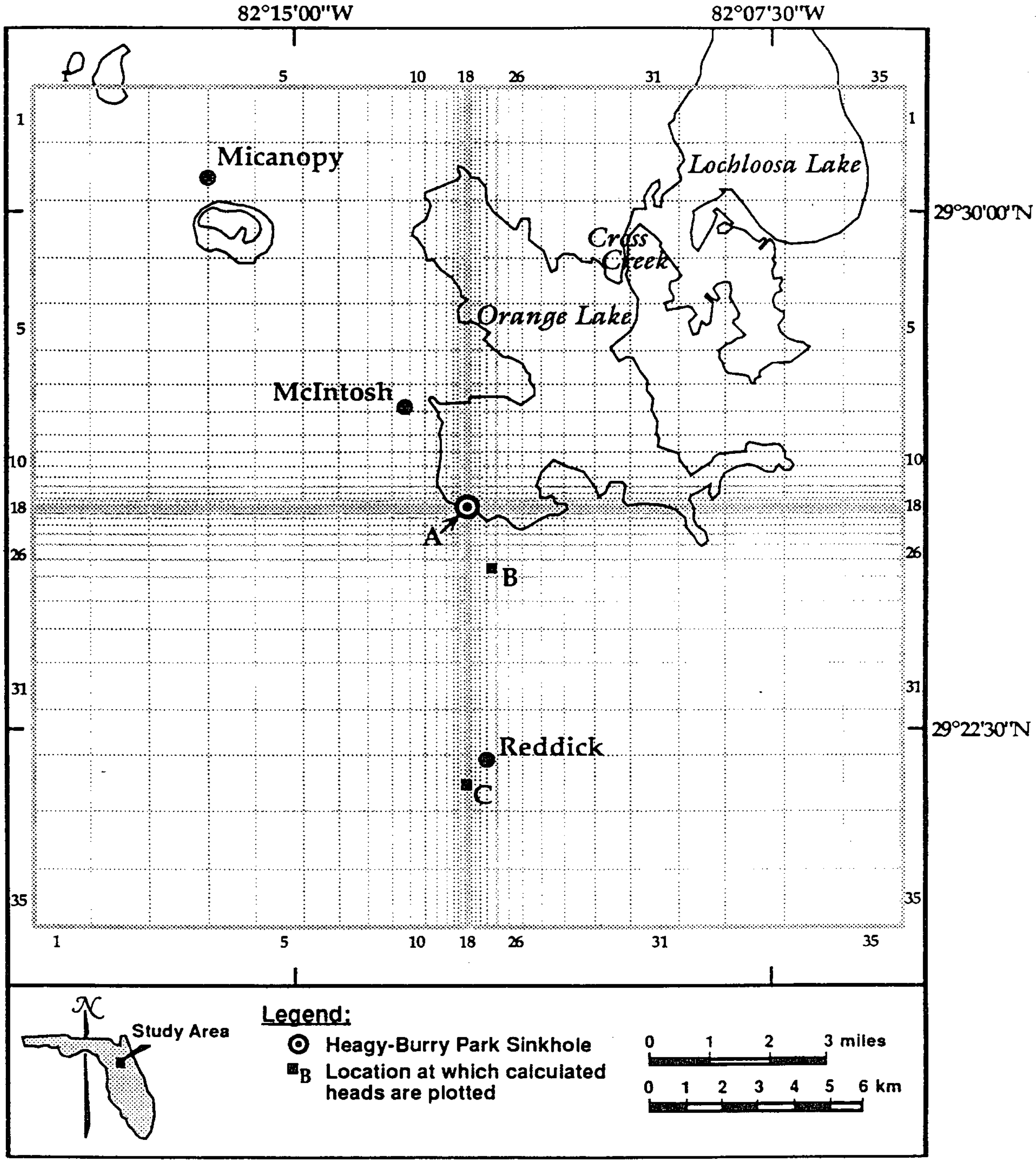


Figure 5-4. Locations A, B, and C at which calculated heads were plotted

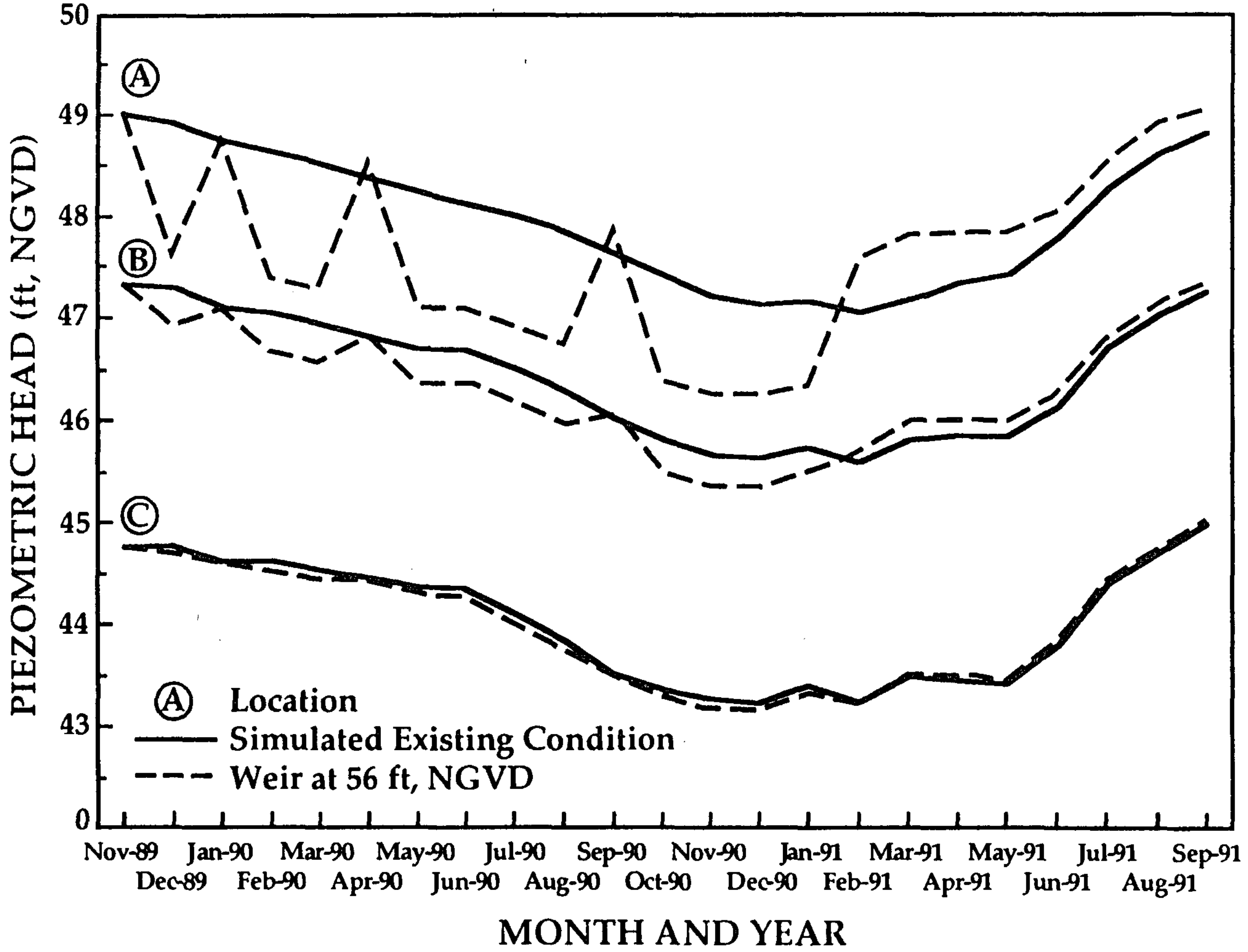


Figure 5-5. Calculated heads in the Upper Floridan aquifer at three locations for simulated existing conditions and for fixed crest weir at 56 ft, NGVD

(see Figure 5-3) will cause an increase in the head in the Upper Floridan aquifer in the vicinity of Orange Lake. The net discharge (inflow-outflow) from Orange and Lochloosa lakes to the ground water system in the November 1989 - September 1991 simulation is reduced from 3.28 × 10^6 ft^3/day (Table 4-6) to 2.78 × 10^6 ft^3/day when the fixed crest weir is maintained at 56 ft, NGVD (see Table 5-6).

Table 5-6. Water budget for the ground water system for the November 1989 - September 1991 simulation when the fixed crest weir is maintained at 56 ft, NGVD

Type of Boundary	Inflow (ft^3 /day)	Outflow (ft^3 /day)
Storage	3.69 × 10^6	3.65 × 10^6
Constant Head	2.39 × 10^6	----
Pumping Wells	----	2.79 × 10^5
Areal Recharge	9.34 × 10^6	----
Evapotranspiration	----	1.23 × 10^5
Lake	2.84 × 10^6	5.54 × 10^4
Head Dependent	2.04 × 10^7	3.46 × 10^7
Total	3.87 × 10^7	3.87 × 10^7

5.3.2 Weir Crest Elevation at 55 ft, NGVD

The case with the fixed crest weir at 55 ft, NGVD, was simulated in a similar manner using the stage levels for Orange and Lochloosa lakes that correspond to this scenario (see Figure 5-3 and Tables 5-4 and 5-5). In this simulation, the area within the sinkhole complex goes dry when the level of Orange Lake drops to 55 ft, NGVD. Also, it was simulated that there is no weir around the sinkhole complex when the lake level is above 55 ft, NGVD. Similar to scenario two with the weir level at 56 ft, NGVD, the impacts that scenario two with the fixed crest weir at 55 ft, NGVD, would have on heads in the Upper Floridan aquifer were calculated using the transient simulation model, and heads in the Upper Floridan aquifer were plotted for locations A, B, and C (see Figure 5-6). The net discharge (inflow-outflow) from Orange and Lochloosa lakes to the ground water system in the November 1989 - September 1991 simulation is reduced from 3.28×10^6 ft^3/day (Table 4-6) to 2.91×10^6 ft^3/day when the fixed crest weir is maintained at 55 ft, NGVD (see Table 5-7).

Table 5-7. Water budget for the ground water system for the November 1989 - September 1991 simulation when the fixed crest weir is maintained at 55 ft, NGVD

Type of Boundary	Inflow (ft^3/day)	Outflow (ft^3 /day)
Storage	3.71×10^6	3.63×10^6
Constant Head	2.40×10^6	----
Pumping Wells	----	2.79×10^5
Areal Recharge	9.34×10^6	----
Evapotranspiration	----	1.23×10^5
Lake	2.99×10^6	7.73×10^4
Head Dependent	2.03×10^7	3.47×10^7
Total	3.88×10^7	3.88×10^7

5.3.3 Weir Crest Elevation at 54 ft, NGVD

Also, the case with the fixed crest weir at 54 ft, NGVD, was simulated using the stage levels for Orange and Lochloosa lakes that correspond to this scenario (see Figure 5-3 and Tables

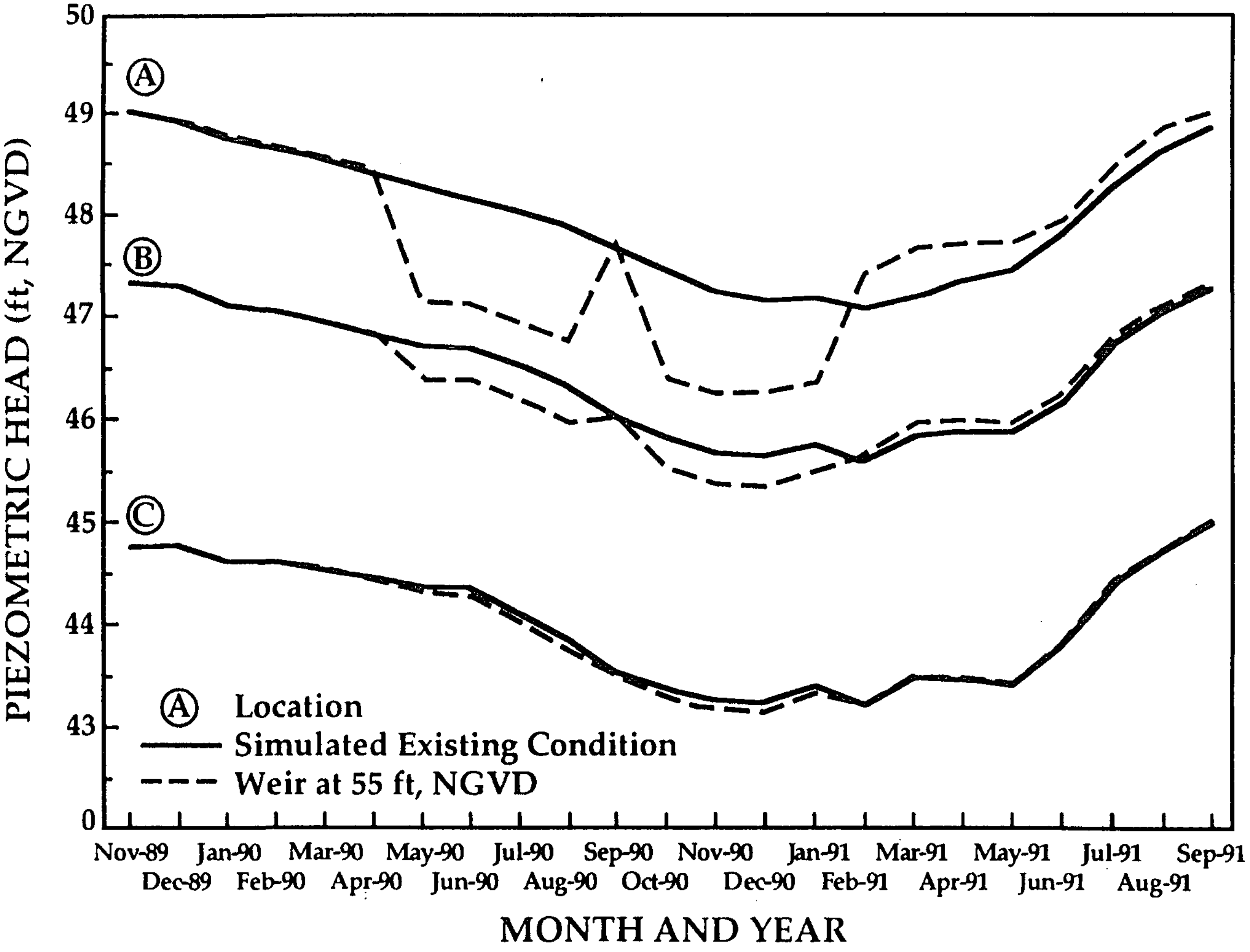


Figure 5-6. Calculated heads in the Upper Floridan aquifer at three locations for simulated existing conditions and for fixed crest weir at 55 ft, NGVD

5-4 and 5-5). In this simulation, the area within the sinkhole complex goes dry when the level of Orange Lake drops to 54 ft, NGVD, and there is no weir simulated around the sinkhole complex when the lake level rises above 54 ft, NGVD. The impacts that this scenario with the fixed crest weir at 54 ft, NGVD, would have on heads in the Upper Floridan aquifer were calculated and plotted for locations A, B, and C (see Figure 5-7). The net discharge (inflow-outflow) from Orange and Lochloosa lakes to the ground water system in the November 1989 - September 1991 simulation is reduced from 3.28×10^6 ft^3/day (Table 4-6) to 3.24×10^6 ft^3/day when the fixed crest weir is maintained at 54 ft, NGVD (see Table 5-8).

Table 5-8. Water budget for the ground water system for the November 1989 - September 1991 simulation when the fixed crest weir is maintained at 54 ft, NGVD

Type of Boundary	Inflow (ft^3/day)	Outflow (ft^3 /day)
Storage	3.72×10^6	3.61×10^6
Constant Head	2.39×10^6	----
Pumping Wells	----	2.79×10^5
Areal Recharge	9.34×10^6	----
Evapotranspiration	----	1.25×10^5
Lake	3.33×10^6	8.90×10^4
Head Dependent	2.02×10^7	3.49×10^7
Total	3.90×10^7	3.91×10^7

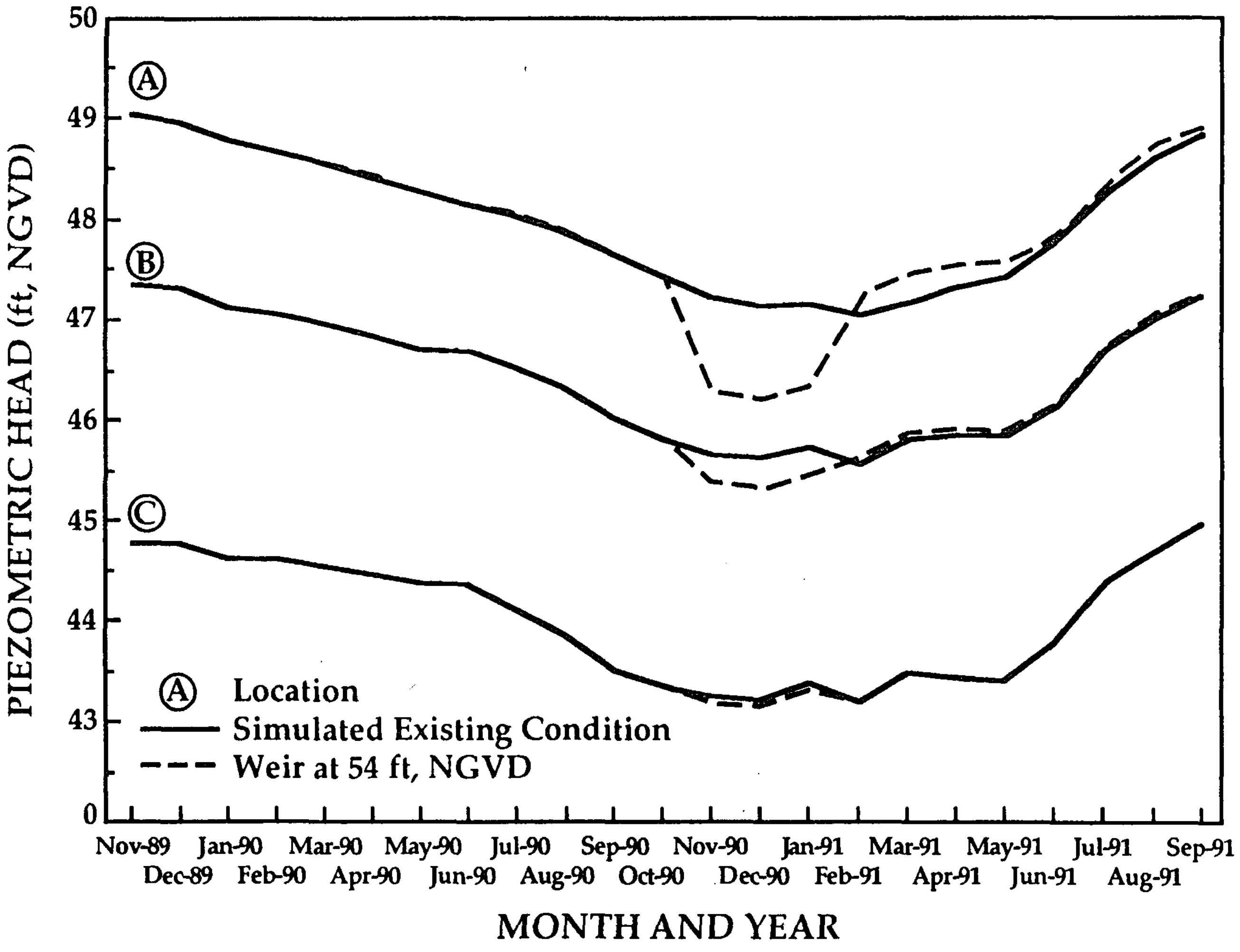


Figure 5-7. Calculated heads in the Upper Floridan aquifer at three locations for simulated existing conditions and for fixed crest weir at 54 ft, NGVD

5.4 ACTIVE CONTROL OF THE SINKHOLE-COMPLEX DISCHARGE WITH A GATED STRUCTURE (SCENARIO THREE)

5.4.1 Gates Kept Open Until Lake Level Drops to 56 ft, NGVD, and Then Gates are Kept Closed Until Lake Level Rises Above 58 ft, NGVD

The transient simulation model described in section 4.6 also was run to simulate active control of the sinkhole-complex discharge. All of the hydrogeologic parameters used in this simulation were the same as in the transient simulation except for the stage levels for Orange and Lochloosa lakes. For this simulation, the stage levels for Orange and Lochloosa lakes simulated by Robinson (1993) for existing conditions and for conditions that corresponded to scenario three with a gated structure closed at 56, 55, and 54 ft, NGVD, were used as input data for the lake levels in the ground water model (see Figure 5-8 and Tables 5-9 and 5-10). In this scenario, it was assumed that the area between the gated structure and the shore would go dry when the gate was closed. It also was assumed that the water level of the lake between the gate and the shore would have the same level as the bottom of the lake except in the cells that represented the sinkhole complex. At those cells, the lake level was assigned a value of 48.5 ft, NGVD, which was the average of the head in the Upper Floridan aquifer at the sinkhole complex for the period of simulation. During the simulation, the water level in the rest of the lake increased until the lake stage rose to 58 ft, NGVD, which was at the end of the simulation.

The impacts that scenario three with a gated structure that was closed when the lake level dropped to 56 ft, NGVD, would have on heads in the Upper Floridan aquifer were calculated using the transient simulation model, and the heads were plotted for the same three locations

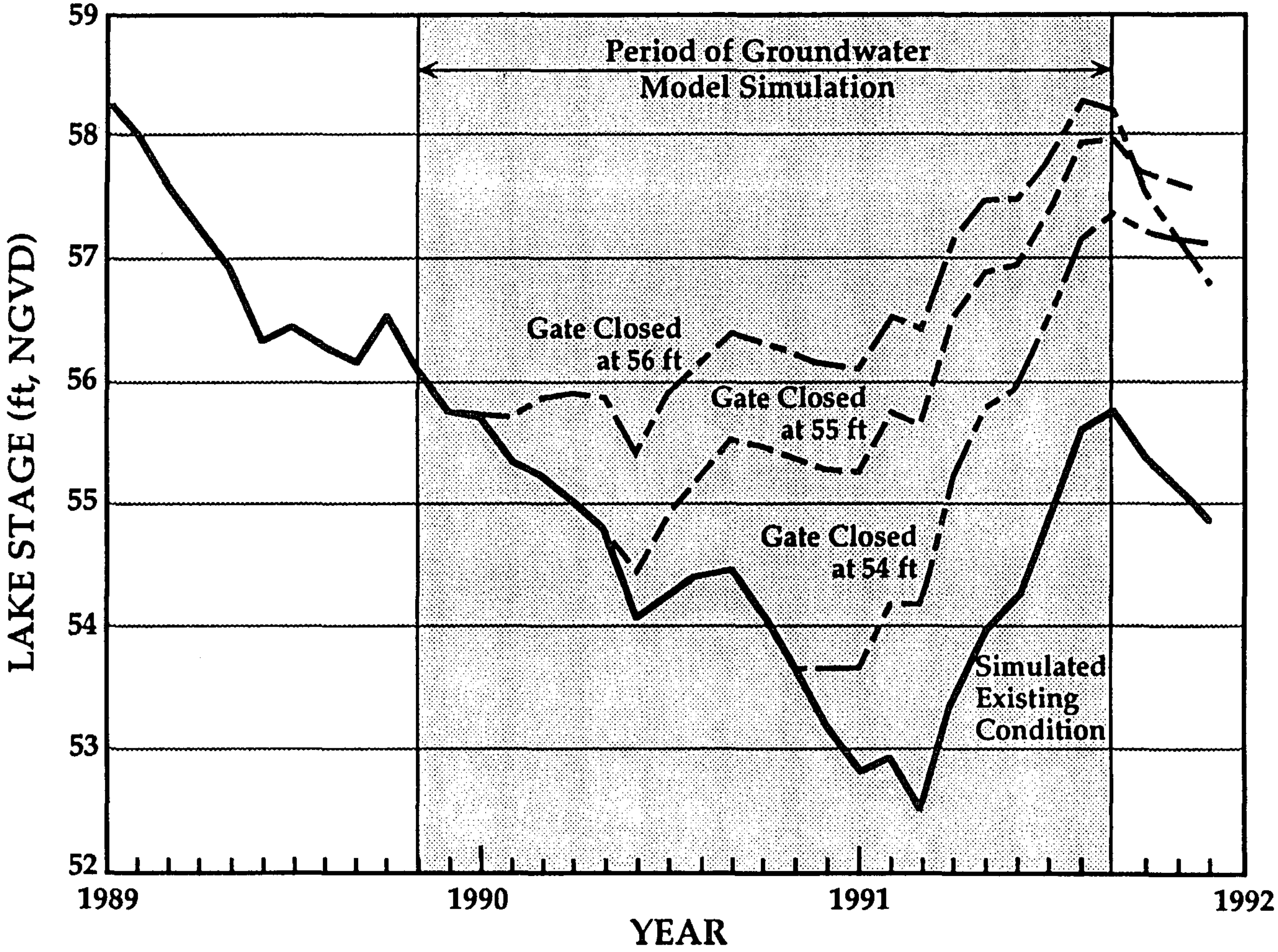


Figure 5-8. Calculated stage at Orange Lake for simulated existing conditions and gated structure scenario (based on Robison et al. 1993)

Table 5-9. Calculated stages for Orange Lake when the sinkhole-complex discharge is controlled by a gate

Date	Simulated Existing Conditions (ft, NGVD)	Gate Closed at 56 ft, NGVD (ft, NGVD)	Gate Closed at 55 ft, NGVD (ft, NGVD)	Gate Closed at 54 ft, NGVD (ft, NGVD)
Nov-89	56.07	56.07	56.07	56.07
Dec-89	55.74	55.74	55.74	55.74
Jan-90	55.70	55.70	55.70	55.70
Feb-90	55.33	55.70	55.33	55.33
Mar-90	55.21	55.84	55.21	55.21
Apr-90	55.02	55.89	55.02	55.02
May-90	54.77	55.86	55.77	55.77
Jun-90	54.07	55.40	55.43	54.07
Jul-90	54.26	55.88	54.89	54.26
Aug-90	54.41	56.15	55.21	54.41
Sep-90	54.46	56.38	55.51	54.46
Oct-90	54.12	56.31	55.47	54.12
Nov-90	53.66	56.20	55.36	53.66
Dec-90	53.24	56.12	55.28	53.65
Jan-91	52.84	56.09	55.26	53.68
Feb-91	52.95	56.53	55.75	54.19
Mar-91	52.52	56.42	55.65	54.18
Apr-91	53.43	57.16	56.52	55.23
May-91	53.97	57.48	56.90	55.78
Jun-91	54.23	57.49	56.95	55.96
Jul-91	54.90	57.82	57.36	56.50
Aug-91	55.60	58.30	57.95	57.16
Sep-91	55.77	58.22	57.97	57.38

Source: Based on Robison et al. 1993

Table 5-10. Calculated stages for Lochloosa Lake when the sinkhole-complex discharge is controlled by a gate

Date	Simulated Existing Conditions (ft, NGVD)	Gate Closed at 56 ft, NGVD (ft, NGVD)	Gate Closed at 55 ft, NGVD (ft, NGVD)	Gate Closed at 54 ft, NGVD (ft, NGVD)
Nov-89	56.43	56.43	56.43	56.43
Dec-89	56.13	56.13	56.13	56.13
Jan-90	56.08	56.08	56.08	56.08
Feb-90	55.69	55.79	55.69	55.69
Mar-90	55.62	55.91	55.62	55.62
Apr-90	55.37	55.87	55.37	55.37
May-90	55.11	55.80	55.11	55.11
Jun-90	54.50	55.30	54.54	54.50
Jul-90	54.88	55.76	54.94	54.88
Aug-90	54.90	56.1	55.24	54.90
Sep-90	54.85	56.26	55.41	54.85
Oct-90	54.58	56.18	55.31	54.58
Nov-90	54.46	56.09	55.24	54.46
Dec-90	54.32	55.99	55.16	54.33
Jan-91	54.25	55.97	55.13	54.25
Feb-91	54.75	56.45	55.71	54.76
Mar-91	54.51	56.32	55.53	54.52
Apr-91	55.21	57.12	56.51	55.43
May-91	55.44	57.60	56.99	56.09
Jun-91	55.13	57.65	57.08	56.15
Jul-91	55.41	58.06	57.54	56.65
Aug-91	55.93	58.54	58.07	57.19
Sep-91	55.98	58.46	58.10	57.28

Source: Based on Robison et al. 1993

(shown in Figure 5-4) that were selected for scenario two. The major impact occurs at the sinkhole complex during the first month after the gate is closed (see Figure 5-9). After that, the impact remains constant, and the heads in the Upper Floridan aquifer follow the same trend as the existing conditions, except that the heads are lower at the sinkhole. The net discharge (inflow-outflow) from Orange and Lochloosa lakes to the ground water system in the November 1989 - September 1991 simulation is reduced from 3.28 × 10^6 ft^3/day (Table 4-6) to 1.42 × 10^6 ft^3/day when the adjustable gate is closed at 56 ft, NGVD (see Table 5-11).

Table 5-11. Water budget for the ground water system for the November 1989 - September 1991 simulation when the adjustable gate is closed at 56 ft, NGVD

Type of Boundary	Inflow (ft^3/day)	Outflow (ft^3 /day)
Storage	3.76 × 10^6	3.53 × 10^6
Constant Head	2.41 × 10^6	----
Pumping Wells	----	2.79 × 10^5
Areal Recharge	9.34 × 10^6	----
Evapotranspiration	----	1.18 × 10^5
Lake	1.47 × 10^6	4.91 × 10^4
Head Dependent	2.08 × 10^7	3.39 × 10^7
Total	3.78 × 10^7	3.79 × 10^7

5.4.2 Gates Kept Open Until Lake Level Drops to 55 ft, NGVD, and Then Gates are Kept Closed Until Lake Level Rises Above 58 ft, NGVD

The case that represents closing the gate when the lake level drops to 55 ft, NGVD, was simulated in a similar manner using the stage levels for Orange and Lochloosa lakes that corre-

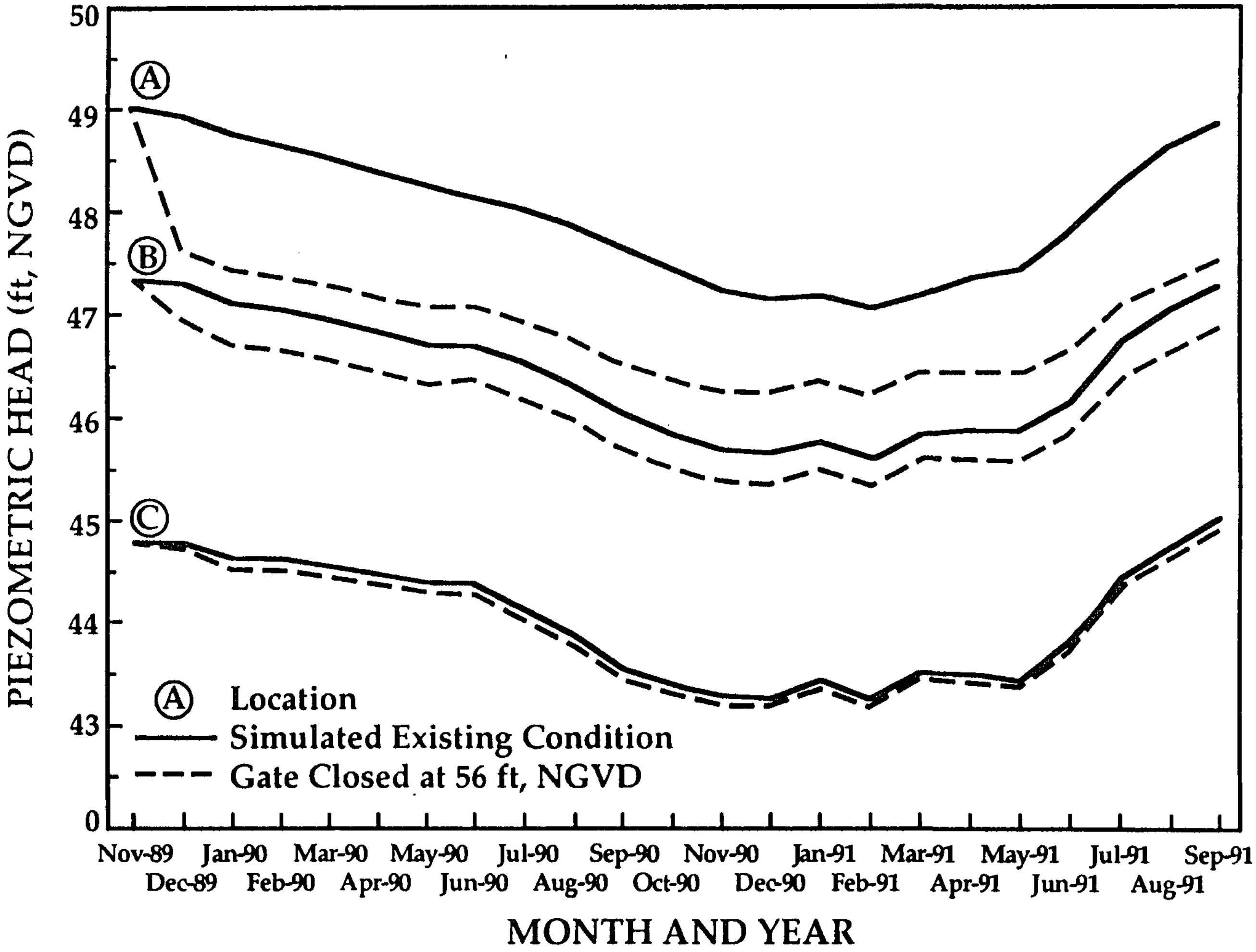


Figure 5-9. Calculated heads in the Upper Floridan aquifer at three locations for simulated existing conditions and for gate closed at 56 ft, NGVD

spond to this scenario (see Figure 5-8 and Tables 5-9 and 5-10). In this simulation, the area within the sinkhole complex goes dry when the gate is closed at a lake level of 55 ft, NGVD. The water level in the rest of the lake increased until the lake stage rose to nearly 58 ft, NGVD, at the end of the simulation. Similar to scenario three with the gate closed at 56 ft, NGVD, the impacts that scenario three with the gate closed at 55 ft, NGVD, would have on heads in the Upper Floridan aquifer were calculated, and the heads were plotted for locations A, B, and C (see Figure 5-10). The net discharge (inflow-outflow) from Orange and Lochloosa lakes to the ground water system in the November 1989 - September 1991 simulation is reduced from 3.28×10^6 ft^3/day (Table 4-6) to 1.90×10^6 ft^3/day when the adjustable gate is closed at 55 ft, NGVD (see Table 5-12).

Table 5-12. Water budget for the ground water system for the November 1989 - September 1991 simulation when the adjustable gate is closed at 55 ft, NGVD

Type of Boundary	Inflow (ft^3/day)	Outflow (ft^3 /day)
Storage	3.78×10^6	3.54×10^6
Constant Head	2.41×10^6	----
Pumping Wells	----	2.79×10^5
Areal Recharge	9.34×10^6	----
Evapotranspiration	----	1.20×10^5
Lake	1.97×10^6	6.80×10^4
Head Dependent	2.07×10^7	3.42×10^7
Total	3.81×10^7	3.82×10^7

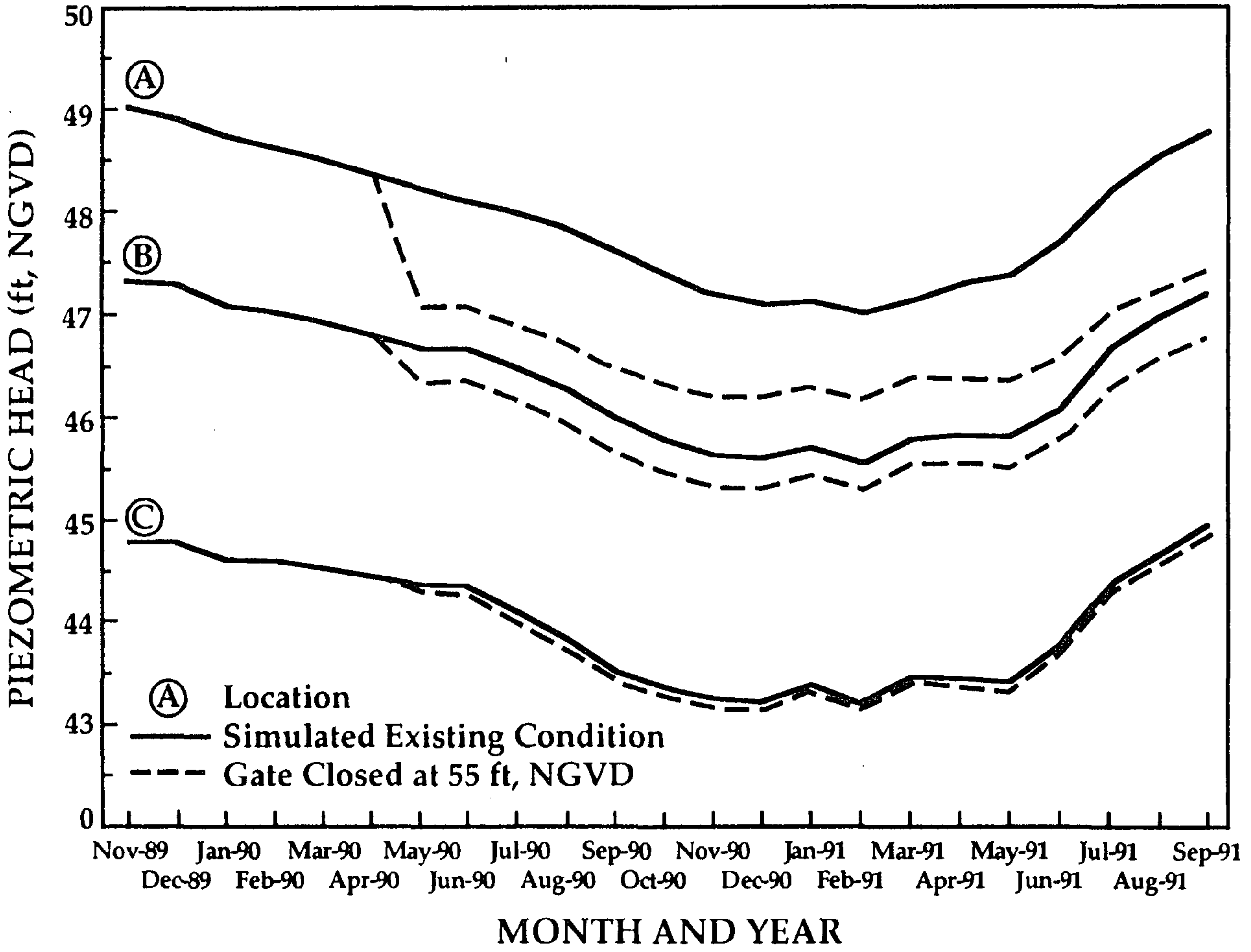


Figure 5-10. Calculated heads in the Upper Floridan aquifer at three locations for simulated existing conditions and for gate closed at 55 ft, NGVD

5.4.3 Gates Kept Open Until Lake Level Drops to 54 ft, NGVD, and Then Gates are Kept Closed Until Lake Level Rises Above 58 ft, NGVD

The case that represents closing the gate when the lake level drops to 54 ft, NGVD, also was simulated using the stage levels for Orange and Lochloosa lakes that correspond to this scenario (see Figure 5-8 and Tables 5-9 and 5-10). In this simulation, the area within the sinkhole complex goes dry when the gate is closed at a lake level of 54 ft, NGVD. The water level in the rest of the lake increased until the lake stage rose to approximately 57.4 ft, NGVD, at the end of the simulation. The impacts that this scenario would have on heads in the Upper Floridan aquifer were calculated and plotted for locations A, B, and C (see Figure 5-11). The net discharge (inflow-outflow) from Orange and Lochloosa lakes to the ground water system in the November 1989 - September 1991 simulation is reduced from 3.28×10^6 ft^3/day (Table 4-6) to 2.31×10^6 ft^3/day when the adjustable gate is closed at 54 ft, NGVD (see Table 5-13).

Table 5-13. Water budget for the ground water system for the November 1989 - September 1991 simulation when the adjustable gate is closed at 54 ft, NGVD

Type of Boundary	Inflow (ft^3 /day)	Outflow (ft^3 /day)
Storage	3.80×10^6	3.52×10^6
Constant Head	2.40×10^6	----
Pumping Wells	----	2.79×10^6
Areal Recharge	9.34×10^6	----
Evapotranspiration	----	1.22×10^6
Lake	2.40×10^6	8.63×10^4
Head Dependent	2.05×10^7	3.45×10^7
Total	3.85×10^7	3.85×10^7

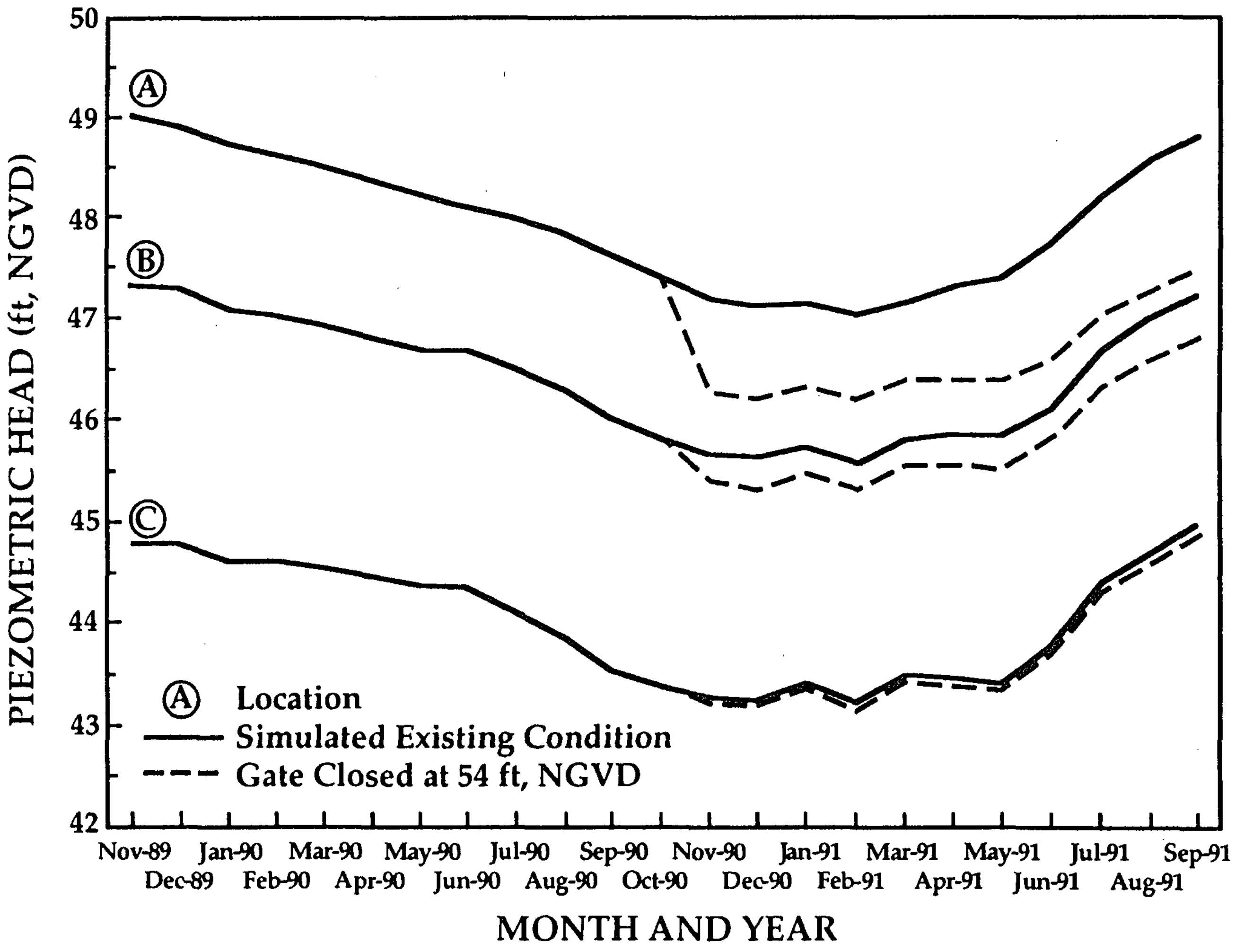


Figure 5-11. Calculated heads in the Upper Floridan aquifer at three locations for simulated existing conditions and for gate closed at 54 ft, NGVD

6.0 CONCLUSIONS

6.1 IMPACTS

The sinkhole-complex discharge-control scenarios described in Chapter 5 were evaluated in terms of their impacts on ground water recharge and geologic stability. For the 1985-1995 period that was considered, the May 1991 low water-level period was considered representative of a drought period, and the September 1988 high water-level period was considered representative of a high rainfall period. The impacts of both spatial and temporal aspects of lake-level and ground water level changes were considered.

6.2 GROUND WATER RECHARGE

Reducing the sinkhole discharge by plugging (or damming) the sinkhole complex or by installing a weir or gate will reduce the net discharge from Orange and Lochloosa lakes to the ground water system and reduce ground water levels in the Upper Floridan aquifer.

For scenario one (in which the sinkhole complex is plugged (or dammed)), during the simulated May 1991 dry period, the maximum decrease in ground water levels in the Upper Floridan aquifer will be 1.54 ft at the sinkhole complex (see Figure 5-1), and the net discharge from Orange and Lochloosa lakes will be reduced from 3.43×10^6 to 3.45×10^5 ft^3/day, or about 89.9 percent (see Table 6-1.) During the simulated September 1988 wet period, the maximum decrease in ground water levels in the Upper Floridan aquifer will be 1.03 ft at the sinkhole com-

Table 6-1. Reductions in net discharge from Orange and Lochloosa lakes to the Upper Floridan aquifer

Scenario	Net Discharge from Lakes to Upper Floridan Aquifer (ft^3/day × 10^6)	Reduction in Net Discharge (percent)
May 1991 dry period (existing conditions)	3.43	---
1.a. May 1991 with sinkhole plugged	0.345	89.9
September 1988 wet period (existing conditions)	2.29	---
1.b. September 1988 with sinkhole plugged	0.255	90.2
Transient simulation for November 1989 to September 1991 (existing conditions)	3.28	----
2.a. Weir crest at 56 ft, NGVD	2.78	15.2
2.b. Weir crest at 55 ft, NGVD	2.91	11.3
2.c. Weir crest at 54 ft, NGVD	3.24	1.22
3.a. Gate closed at 56 ft, NGVD	1.42	56.7
3.b. Gate closed at 55 ft, NGVD	1.90	42.1
3.c. Gate closed at 54 ft, NGVD	2.31	29.6

plex (see Figure 5-2), and the net discharge from the lakes will be reduced from 2.29×10^6 to 2.25×10^5 ft^3/day, or about 90.2 percent (see Table 6-1).

For scenario two, in which a fixed crest weir is installed to maintain passive control of the discharge, the greatest impact on ground water levels will be due to scenario 2.a. In this scenario, the weir is set at 56 ft, NGVD, and the decrease in the ground water level in the Upper Floridan aquifer at the sinkhole complex will be slightly greater than 1 foot (see Figure 5-5). The net discharge from Orange and Lochloosa lakes to the ground water system will be reduced from 3.28×10^6 to 2.78×10^6 ft^3/day, or about 15.2 percent (see Table 6-1). For scenarios 2.b. and 2.c., in which the weir is set at 55 and 54 ft, NGVD, respectively, the impacts on ground water levels will be less. The duration of the ground water level changes will be shorter (see Figures 5-6 and 5-7), and the reductions in net discharge from the lakes will be about 11.3 and 1.2 percent, respectively (see Table 6-1).

For scenario three, in which a gate is operated to maintain active control of the discharge from the sinkhole complex, the greatest impact on ground water levels will be due to scenario 3.a. In this scenario, the gate will be closed when the lake level drops to 56 ft, NGVD, and opened when the lake level rises to 58 ft, NGVD. The decrease in the ground water level in the Upper Floridan aquifer at the sinkhole complex will be about 1 foot (Figure 5-9). The net discharge from Orange and Lochloosa lakes to the ground water system will be reduced from 3.28×10^6 to 1.42×10^6 ft^3/day, or about 56.7 percent (see Table 6-1). For scenarios 3.b. and 3.c., in which the gate is closed when the lake level drops to 55 and 54 ft, NGVD, respectively, and opened at 58 ft, NGVD, the impacts on ground water levels will be less. The duration of the ground water level changes will be shorter (see Figures 5-10 and 5-11), and the reductions in discharge from the lakes will be about 42.1 and 29.6 percent, respectively (see Table 6-1).

In all of the scenarios, the greatest impact that controlling the sinkhole-complex discharge will have on ground water levels in the Upper Floridan aquifer will be at the sinkhole complex, where the maximum decrease will be on the order of about 1.5 ft. The impact will diminish spatially and be negligible within a few miles from Orange Lake (see Figures 5-1, 5-2, 5-5, 5-6, 5-7, 5-9, 5-10, and 5-11). Under existing conditions, the difference between the September 1988 high ground water level and the May 1991 low ground water level was 7.5 ft at the Heagy-Burry Park sinkhole complex (see Figure 3-4). Thus, the maximum changes in ground water levels that would be associated with controlling the sinkhole-complex discharge are on the order of 20 percent of the changes that occurred between the natural highs and lows during the 1985-1995 period of evaluation.

6.3 GEOLOGIC STABILITY

The impact that controlling the sinkhole-complex discharge will have on geologic stability was evaluated in terms of geologic and hydrologic criteria. These criteria were based on the hydrogeologic profiles developed during the investigation, changes in lake levels, spatial impacts of the scenarios, the magnitude of ground water level fluctuations in the Upper Floridan aquifer, existing sinkhole and karst features in the study area, the extent of unconfined conditions in the Upper Floridan aquifer, and characteristics of the overlying confining unit where it is present.

Scenario two most likely will have the greatest impact on geologic stability. Lake-level increases above existing conditions will be greatest for scenario 2.a., in which the weir will be set at 56 ft, NGVD (see Figure 5-3). Relatively rapid and repeated transient changes are predicted to occur in ground water levels in the Upper Floridan aquifer at the sinkhole complex for this scenario (see Figure 5-5), which thus will have the greatest impact on geologic stability. The impacts will be less for scenarios 2.b. and 2.c., in which the transient changes in ground water levels also will occur but will be less than in scenario 2.a. (see Figures 5-6 and 5-7).

Scenario three likely will have an intermediate impact on geologic stability. Lake-level increases above existing conditions will be greatest for scenario 3.a. (see Figure 5-8), and also the duration of ground water level decreases will be greatest within this scenario (see Figure 5-9). Ground water level decreases also are predicted for scenarios 3.b. and 3.c., but the duration of these changes will be less (see Figures 5-10 and 5-11), and thus the impact on geologic stability also will be less.

Scenario one likely will have the least impact on geologic stability. The maximum predicted decrease in the ground water level in the Upper Floridan aquifer (see Figures 5-1 and 5-2) is greater than in the other scenarios, but this scenario does not involve superimposing additional transient changes on ground water levels in the Upper Floridan aquifer.

6.4 RECOMMENDATIONS

In this project, the geologic and hydrologic aspects of controlling the discharge at the Heagy-Burry Park sinkhole complex were investigated. The maximum reduction in ground water levels in the Upper Floridan aquifer due to the discharge-control scenarios is on the order of 20 percent of the 1985-1995 natural seasonal fluctuations in ground water levels in the Upper Floridan aquifer. Significant reductions in the net discharge from Orange and Lochloosa lakes (about 90 percent of which occurs at the sinkhole-discharge complex) to the Upper Floridan aquifer will occur, particularly in scenarios 1.a, 1.b, 3.a, and 3.b, and to a lesser extent in the other scenarios. Intense transient changes, particularly the rapid and repeated transient changes associated with scenario 2.a., should be avoided, i.e., there should be no rapid artificial control of Orange Lake, the ground water levels in the Upper Floridan aquifer, or the discharge from Orange Lake to the Upper Floridan aquifer. It is important to recognize that investigating the structural aspects of the proposed scenarios was not in the scope of this investigation and thus was not addressed. At this point, if one or more of the scenarios is to be considered further, detailed geotechnical studies and hydrogeologic characterization of the sinkhole complex need to be performed to determine the characteristics of the bottom of Orange Lake in the vicinity of the sinkhole complex. Also, additional hydrologic studies should be performed to investigate the impacts that extreme drought and wet periods (such as occurred in 1956 and 1941, respectively) would have on the proposed scenarios. This could be achieved by investigating where the demarcation lines (described in chapters three and four) would be located under such conditions. The probability of other (but now inactive) paleo-sinkhole complexes should be examined thoroughly in this extended zone.

7.0 REFERENCES

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