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A WATER RESOURCE ANALYSIS OF THE JENSEN BEACH PENINSULA, MARTIN COUNTY, FLORIDA

by

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EXECUTIVE SUMMARY

The relationships between wetlands, surface water management lakes, hardpan and wellfield withdrawals have long been an issue on the Jensen Beach peninsula. This study was undertaken to provide technical information on these relationships, and to develop a tool for estimating the effects of ground water withdrawals on the overlying wetlands on the peninsula.

Hydrogeologic Regime

The Surficial Aquifer System on the Jensen Beach peninsula consists primarily of undifferentiated deposits of varying lithology. From the surface to 40 to 80 feet below land surface, the lithology consists primarily of quartz sand interspersed with shell beds. Underlying the sand is the principal producing zone of the aquifer consisting of 50 to 140 feet of interfingering beds of sand, shell, and sandy limestone. The north Martin County wellfield (NMCW) produces water from this zone.

The sand layer normally contains one or more hardpan units (layers of low permeability composed primarily of fine sand and organic material) within a few feet of land surface. It was commonly thought that this hardpan formed a continuous barrier to downward leakance, creating a perched wetland system. It was found in this study, however, that the hardpan was not a continuous, uniform layer. Where present, the hardpan varied greatly in thickness and depth over small distancesl; often dipping, thinning and disappearing, all within a single wetland. It was concluded that although hardpan layers are frequently present, they have variable leakance characteristics and are spatially discontinuous. The hardpan does not completely isolate the wetlands from the rest of the aquifer. Therefore, the wetlands can be impacted by wellfield withdrawals.

Ground Water Flow Model

A three-dimensional ground water flow model of the Surficial Aquifer System on the Jensen Beach peninsula was developed using the U. S. Geological Survey modular three-dimensional ground water flow model, commonly known as MODFLOW. The model was calibrated against meteorologic and water level data from the period February 1987 - December 1989, and was used to quantify water availability and ground water drawdowns under different meteorologic and management scenarios.

Wetland Impacts Due to Withdrawals from the North Martin County Wellfield

The Regulation Department of the South Florida Water Management District (SFWMD) uses a guideline of one foot of wellfield induced drawdown under wetlands as an indicator of possible adverse impacts to the wetland. Model simulations have shown as much as four feet of drawdown under some isolated wetland areas as a result of pumping from the NMCW. Wetland water levels were found to be most sensitive to pumping from wells 7 and 10, and least sensitive to pumping from wells 6 and 9.

The issue of wetland impacts was further studied using the SFWMD's wellfield optimization model, MODMAN. When used in conjunction with a calibrated MODFLOW model, MODMAN yields optimal solutions to explicitly stated water management problems. MODMAN was configured to determine the maximum yield which can be obtained from the current wellfield without inducing more than one foot of drawdown under any wetland area. The results of the MODMAN simulations indicated that it is not possible to rearrange pumping from the existing wellfield to meet the one foot guideline if the utility continues at its present allocation of 2.5 million gallons of water per day.

Martin County Utilities is in the process of developing a reverse osmosis (RO) facility in order to shift withdrawals from the Surficial Aquifer System to the deeper Floridan Aquifer System. However, current SFWMD regulations restrict the use of pumps on wells tapping the Floridan Aquifer System in Martin and St. Lucie counties as a means to maintain the potentiometric levels above land surface. This restriction may have to be modified if the Floridan Aquifer System is to be a practical source for public water supply. Problems also exist in regard to the safe disposal of the brines which result from the reverse osmosis procedure.

Despite these potential problems, the use of Floridan Aquifer System water is deemed to be the most practical alternative to north Martin County's water supply problems. It is recommended that the utilities' Surficial Aquifer System permitted allocation be reduced as the desalination plant comes on line. Future requests for additional withdrawals from the Surficial Aquifer System by others should be evaluated to determine if they will cause adverse impacts to wetlands.

Wetland Impacts Due to Hardpan Piercing Activities

Since it was commonly thought that the hardpan isolated the wetlands from the aquifer, concerns were raised about activities that pierce the hardpan, such as the construction of surface water management lakes. These lakes are typically used to detain or retain storm water runoff, as required by District regulatory criteria. The Regulation Department of the SFWMD has a regulatory criteria restricting construction of surface water management lakes within 200 feet of a wetland.

Although the hardpan in the vicinity of the NMCW does not serve to totally isolate the wetlands from the rest of the aquifer, the criteria regulating construction of surface water management lakes within 200 feet of wetlands piercing activities still has merit. The presence of the hardpan unit has led to the occurrence of a perched water table at numerous locations on the Jensen Beach peninsula. These localized perched conditions tend to dissipate over time through the influence of evapotranspiration and downward percolation. Hardpan piercing activities lead to an increased rate of downward percolation and alter the natural dry/wet cycle of a wetland.

In addition to reducing the rate of downward percolation, a low permeability hardpan layer promotes horizontal movement of water (interflow). Water flows slowly across the undulating hardpan surface until it enters a discharging area. A discharge area can be any depressional feature (e.g. stream, ditch, wetland or surface water management lake). This interflow is a source of recharge to wetland areas. Excavations upslope from a wetland area may impact it by intercepting the interflow which would ordinarily have provided recharge to the wetland.

Because the hardpan layer induces a greater component of horizontal flow, a separation of 200 feet between an excavation and a wetland area, as is currently required by SFWMD criteria, will not always be sufficient to prevent impacts. Excavations cause localized drawdowns in water level elevations which in turn causes an increase in the amount of horizontal flow. As the amount of horizontal flow increases, so does the lateral extent of the area which an excavation may impact. Further study is needed to develop criteria to determine reasonable distances between surface water management lakes and wetlands for a variety of situations. Critical factors would include the hydraulic conductivity of the soil and the slope of the hardpan layer.

Recommendations

1. Pumpage from the Surficial Aquifer System in north Martin County should be optimized in order to minimize impacts on the wetlands. Permitted allocations should be modified to reflect the optimized withdrawals. In addition, permitted allocations should be further reduced as water from the desalinization plant becomes available.

2. The SFWMD should complete an evaluation of the Floridan Aquifer System as a source of public water supply. The District's criteria restricting installation of pumps on Floridan wells in Martin and St. Lucie counties should be reviewed. Other alternatives to the Surficial Aquifer System, such as conservation and reuse, should be encouraged.

3. The relationship between surface water management systems, hardpan layers, and ground water levels needs further study. Results of this further study should be used to modify the regulatory criteria governing the construction of surface water management systems.

4. Information on 1) the interrelationship between wetlands and ground water levels, 2) leakance between the Surficial Aquifer System and the mid-Hawthorn confining unit, and 3) domestic withdrawals in the Jensen peninsula should be incorporated into the model as it becomes available.

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ABSTRACT

The Jensen Beach peninsula, located in northeastern Martin County, is bordered on three sides by saline water. At the center of the peninsula is a municipal wellfield, permitted to withdraw 2.5 mgd from the Surficial Aquifer System. Over the past few years, the area has experienced a steady decline in the ground water levels. During this time, water levels in small wetlands scattered across the peninsula have been declining as well. This study was designed to determine the relationship between wellfield pumping and water levels in wetlands. A three-dimensional flow model of the Surficial Aquifer System has been developed using the U.S. Geological Survey MODFLOW code. The model comprises two layers, corresponding to a shallow sand layer and a deeper layer of sand, shell, and limestone, in which the wellfield is finished. Areally, the aquifer is represented by a finite difference grid of 96 rows by 98 columns. The initial aquifer parameters were determined by a study of lithologic well logs and pumping tests from recent reports. Final aquifer parameters used in the model are a layer one hydraulic conductivity of 23 ft/day, specific yield of 0.18; and layer two hydraulic conductivity of 30 ft/day and a storage coefficient 0.0004. These values are within the range of values obtained in aquifer performance tests. Vertical conductance between the two model layers was calculated as a function of the vertical hydraulic conductivity and layer thickness. A transient calibration was made by comparing computed heads against observed water levels in the saltwater intrusion monitoring wells belonging to the water utility. Predictive simulations were run with the model to determine a wellfield operational strategy that would allow maximum withdrawals without causing excess drawdowns under wetland areas. The model simulations indicated that it is not possible for the wellfield to pump at its current permitted allocation of 2.5 mgd without causing drawdowns of more than one foot under some wetlands, which would violate District regulatory criteria. An alteration in the permitted allocation from the wellfield is recommended to alleviate wetland impacts.

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INTRODUCTION

The relationships between wetlands, water management lakes, hardpan and wellfield withdrawals have long been an issue on the Jensen Beach peninsula, located in northeast Martin County (Figure 1). This study was undertaken to provide technical information on these relationships, and to provide a tool for estimating the effects of ground water withdrawals on the overlying wetlands on the peninsula.

In 1978 Martin County Utilities was issued a permit to install a public water supply wellfield and water treatment plant on the Jensen Beach peninsula. This facility came on line in 1983, with a permit to withdraw .92 billion gallons per year (bgy) (2.52 mgd) from the Surficial Aquifer System.

In December of 1985, the SFWMD presented the Martin County Board of Commissioners with the Martin County Water Resources Assessment (MCWRA), which was later published by the SFWMD (Nealon et al., 1987). This document was designed to provide the county with a regional analysis of water availability, and water resource planning recommendations that could be used for future growth management strategies. Included in the report were concerns over the possible impacts of existing ground water withdrawals from the north Martin County Wellfield on overlying wetland areas located in and around the wellfield (Figure 2). Since the permitted allocation was only one-third of the projected water demand at buildout, the possibility of extensive impacts to the wetlands existed. In addition, concern was raised regarding the role of the hardpan, a discontinuous, shallow, low permeability organic sand layer, in minimizing drawdown impacts on wetlands. Construction of surface water management lakes pierce the hardpan layer, and concerns were raised about the possibility of draining the wetlands through these breaches in the hardpan. The SFWMD has a regulatory criteria restricting construction of surface water management lakes within 200 feet of wetlands.

As a result of the MCWRA, the role of the hardpan in the retardation of water movement became a topic for heated debate. Proponents of increased wellfield withdrawals argued that the hardpan layer totally isolated the wetlands from the rest of the aquifer, creating a perched wetland system. Therefore, withdrawal of water from the aquifer would not impact the wetlands. On the other hand, those desiring the construction of hardpan perforating surface water management lakes, contended that the wetlands were not perched, but fed by the water table. Therefore, any number of lakes could be dug through the hardpan without impact to the wetlands.

When Martin County Utilities requested an increase of their Surficial Aquifer System allocation to 1.37 bgy (3.75 mgd), it was not approved. They decreased the request to 1.1 bgy (3.0 mgd), but because the issue of impacts to adjacent wetlands had not been sufficiently resolved, the additional allocation was not approved. The permitted allocation remains at 2.5 mgd. By the early part of 1989 it had become apparent to both SFWMD and Martin Utilities personnel that wetland impacts not withstanding, there was insufficient capacity in the Surficial Aquifer System to meet buildout demand for the peninsula. The County conducted a study to evaluate the alternatives of constructing additional surficial wells west of the North Fork of the St. Lucie River, or going to desalination of Floridan Aquifer System water. They opted for desalination, obtained permits, and initiated well construction in the fall of 1989.

PURPOSE AND SCOPE

Since Martin County Utilities is turning to desalination, they will receive a decreased Surficial Aquifer System allocation. This is a result of a limiting condition on their water use permit which requires reducing the allocation from the Surficial Aquifer System as the desalination plant comes on line. However, the questions regarding the relationships between wetlands, hardpan, and the production zone are

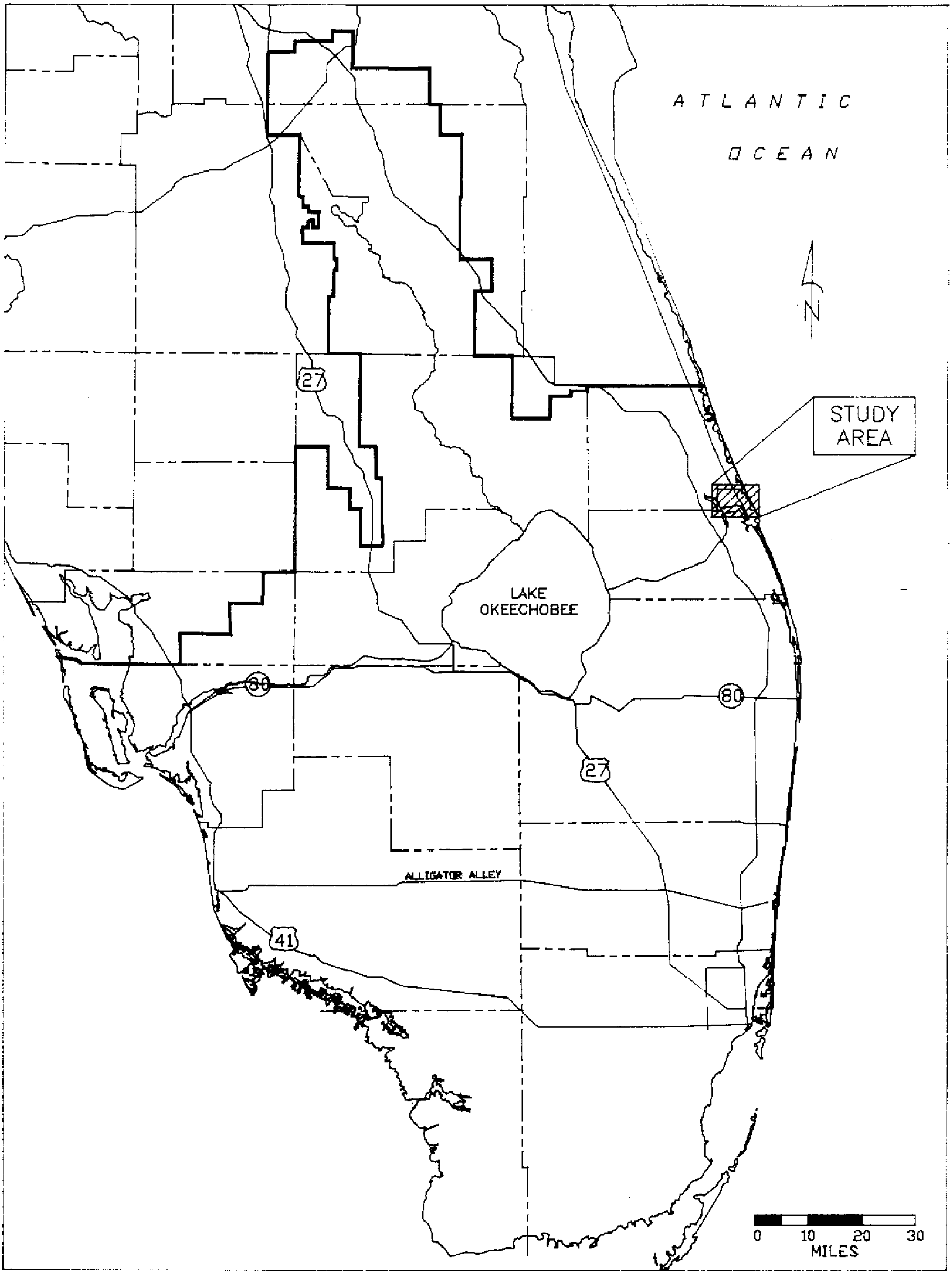

FIGURE 1. Location of Study Area.

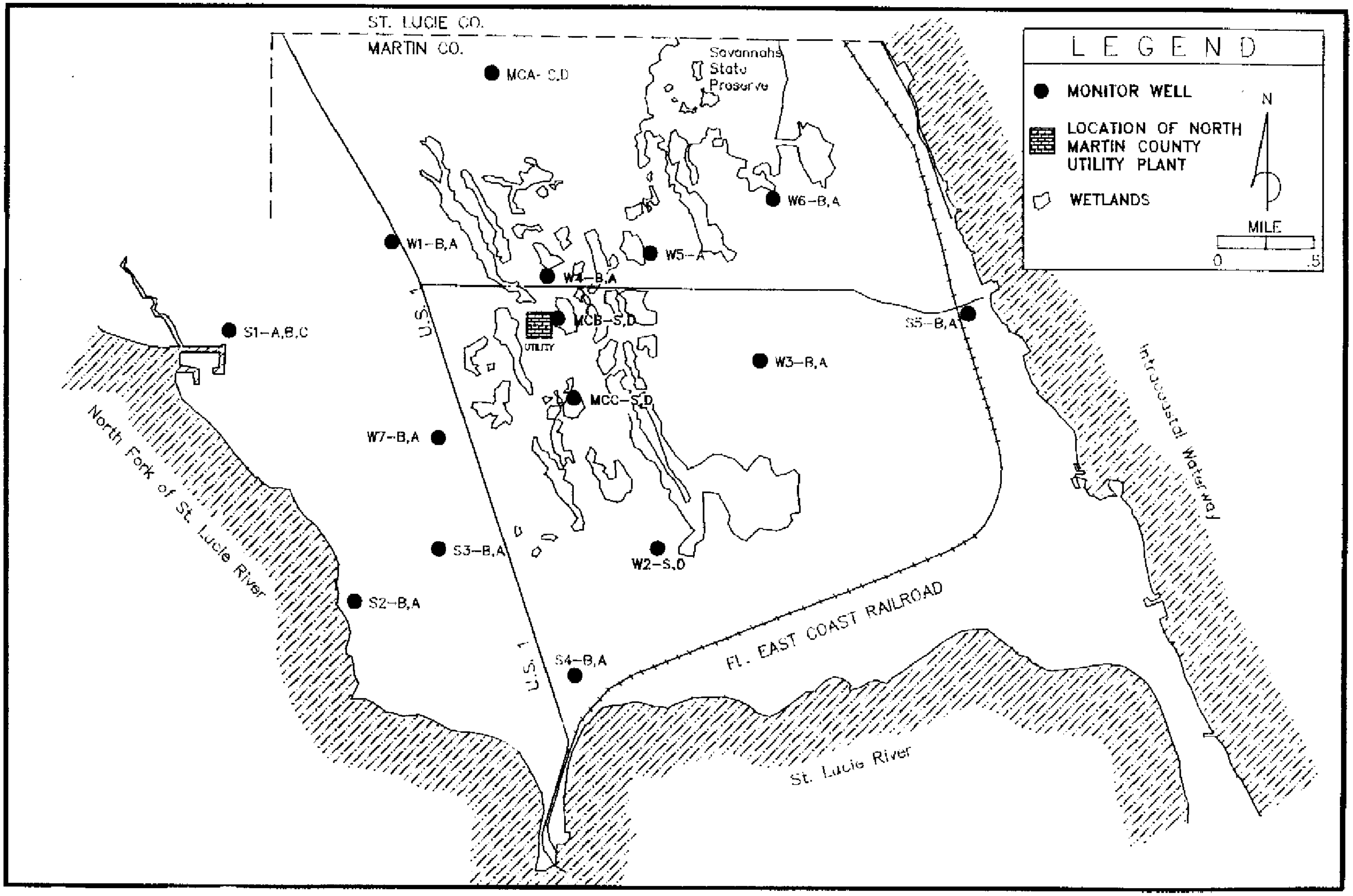

FIGURE 2. Map of Study Area Showing Location of Wetlands and Monitoring Wells.

still valid, particularly with regard to the construction of surface water management lakes. Because the hydrogeologic system in the vicinity of the north Martin County wellfield is typical of that found in other growth potential areas of Martin and St. Lucie counties, problems similar in nature to those experienced in the Jensen Beach peninsula may be expected in those areas as well.

This study was undertaken for the purpose of providing technical information regarding the interrelationship between the hardpan layer and the Surficial Aquifer System, and to provide a tool for estimating of the effects of ground water withdrawals on the overlying wetlands of the Jensen Beach peninsula.

The study was divided into three phases. The first two phases, consisted of: 1) a compilation of existing geologic and hydrologic data from the Jensen Beach area, and 2) field data acquisition consisting of water level and rainfall monitoring and completion of an aquifer performance test, for the purpose of determining the hydraulic characteristics of the aquifer and hardpan unit. Phase I and II of this study were completed under contract with James M. Montgomery Consulting Engineers, Inc. (JMM). Phase III of the study (completed by SFWMD) consisted of an evaluation of the data collected in phases I and II and development, calibration, and application of a three-dimensional ground water flow model.

In addition to data collection and analysis, a number of issues regarding water management and water use practices in the area needed to be addressed. A list of questions was developed by SFWMD to address the effects of ground water use in the study area (Figure 2). These questions are listed below and constitute the scope of the study.

1. Is there any validity to the concern over the effects of hardpan perforating activities on adjacent wetland areas? Can the effects be quantified?

2. Is the existing operational strategy of the NMCW optimum? How might it be modified in order to minimize wetland impacts?

3. Is the current well configuration of the NMCW optimum, or can it be modified to minimize effects on wetlands or residential lakes?

4. Is there a hydrologic link between the NMCW and the Savannas State Preserve?

5. What factors have contributed to the dry conditions and lower than average surficial aquifer levels in the Jensen Beach area?

MODEL DEVELOPMENT

The Surficial Aquifer System (SAS) in the vicinity of the north Martin County Wellfield was modeled using the USGS three-dimensional finite-difference ground water flow code MODFLOW (McDonald et al., 1984). MODFLOW is essentially a water budget program based on Darcy's Law and the equation-of continuity, which when applied to aquifer systems can be written as: Inflow - Outflow = Change in Storage. The finite difference method depends upon the discretization of the region of flow into a finite number of blocks (cells), each having uniform hydrogeologic properties. The hydraulic head for the entire cell is defined at its center or node. Figure 3 illustrates flow into and out of a typical model cell.

Data sets for all MODFLOW packages used during transient calibration are available on floppy disk upon request. Table 1 lists the MODFLOW packages used for the north Martin County model.

HYDROGEOLOGIC REGIME

The Surficial Aquifer System in the vicinity of the north Martin County wellfield is composed primarily of unconsolidated deposits of varying lithology. From the surface to 40 to 80 feet below land surface, the lithology consists of white to brown quartz sands interbedded with shell layers. The surficial sands normally contain one or more "hardpan" units (layers of low permeability composed primarily of fine sand and organic material) within a few feet of land surface.

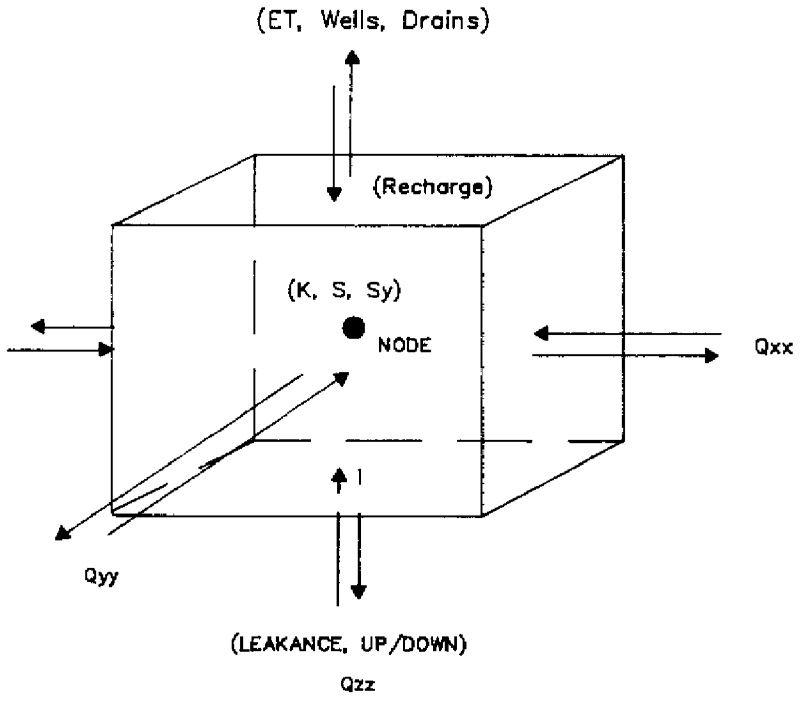

FIGURE 3. Unit Cell Showing Inflows, Outflows and Physical Properties.

TABLE 1: PACKAGES IN MODFLOW USED IN THE NORTH MARTIN COUNTY MODEL

MODFLOW PACKAGE	FUNCTION	MODEL USE
BASIC	Model Administration	Used
BLOCK CENTERED FLOW	Computation of conductance and storage components of finite-difference equations	Used
RECHARGE	Simulates recharge to the aquifer from infiltration of precipitation	Used with measured rainfall assuming 50 to 70% infiltration to the surficial aquifer
WELL	Simulates a source/sink to the aquifer that is not affected by heads in the aquifer	Used to represent discharge from N. Martin County Utilities wells and other users with individual SFWMD permits
DRAIN	Simulates discharge from the aquifer to drains.	Used to represent Howard Creek and major drainage ditches near observation wells
EVAPOTRANSPIRATION	Simulates evapotranspiration where the source of water is the saturated porous medium.	Used to represent ET, with maximum monthly rates ranging from 2.5-6" at land surface declining non-linearly to zero at a depth of 4', with a 1' capillary fringe.
STRONGLY IMPLICITY PROCEDURE (SIP)	Solve the model's finite difference equations using the Strongly Implicit Procedure	Used

It was commonly thought that this hardpan formed a continuous barrier to downward leakance, creating a perched wetlands system. However, soil borings obtained from four wetlands of representative soil types indicated that the deeper marsh soils lacked a hardpan layer. Where present, the hardpan was found to vary greatly in thickness and depth over very small distances, dipping, thinning and disappearing, all within the same wetland. In general, it was found that though low permeability "hardpan" layers are frequently present within the soil profile, they have variable leakage characteristics and are spatially discontinuous (JMM, 1988).

DISCRETIZATION

Horizontal

The study area with the model grid used in this analysis is shown in Figure 4. Because the wetlands in the vicinity of the wellfield are small, a large grid cell size would make it impossible to view them as discrete features. It was necessary, therefore, to choose a cell size that would be small enough to represent individual wetlands. On the other hand, as the cell size decreases, the data input needed for the model becomes more intensive, and computational limitations become a constraint. A cell dimension of 240 by 240 feet was chosen for most of the model as a balance between these two opposing considerations. Beginning in row eight, the cell length expands to the northwest, away from the main area of interest, by a factor of 1.5 times per row (see Figure 4). The dimensions of the grid are 96 rows by 98 columns. Further discussion regarding cell dimensions is included in the section on boundary conditions.

Vertical

The physical characteristics of the Surficial Aquifer System, and the overlying hardpan and wetlands, were determined from a review of all available hydrogeologic data. The bulk of this information was obtained from Phases I and II of the JMM report and South Florida Water Management District (SFWMD) investigations.

Based on lithologic data collected from the 32 well logs in the area (Figure 5), the model was discretized into two layers. The top layer represents that portion of the aquifer which is composed of medium to fine grained sand, which tends to grade finer with depth. This surficial sand layer ranges in thickness from 40 feet in the vicinity of the wellfield to upwards of 80 feet on the eastern edge of the study area in the sandhills of the Atlantic Coastal Ridge. Interbedded lenses of sandy clay and silt are present at the base of this unit in some areas.

Underlying the sand is the principal producing zone of the aquifer, 50 to 140 feet of interfingering beds of sand, shell, and sandy limestone producing from 200 to 300 gallons of potable water per minute. This zone, comprising layer two of the model, was separated from the surficial sand layer on the basis of its higher transmissivity. Both layers tend to dip and thicken to the east and south.

Semi-permeable clays and marls unconformably underlie and form the base of the Surficial Aquifer System (Lichtler, 1960). Miller (1980) places the altitude of the base of the Surficial Aquifer between -160 and -180 feet NGVD within the study area. These values are based on the elevation of the top of the Hawthorn Group (green, phosphatic, clayey sand) in USGS wells M-1023, M-1043 and SL-175. Lithologic review of additional wells within the peninsula indicated that the base of the actual producing zone was considerably higher, due to the increasing presence of clay and silty lenses near the top of the Hawthorn Group. The bottom of the model (bottom of layer 2) was defined as the bottom of the producing zone.

MODFLOW requires each layer of a model to be classified as either confined, unconfined, or fully or partially convertible between confined and unconfined. Both layers one and two are part of the unconfined, or water table aquifer, though flow between the two is sluggish due to the presence of fine material near the base of layer one. However, MODFLOW does not allow the designation of more than one unconfined layer in a model. For this reason, layer one was defined as unconfined, and layer two was designated as partially convertible between confined and unconfined. These designations determine the way in which heads will be

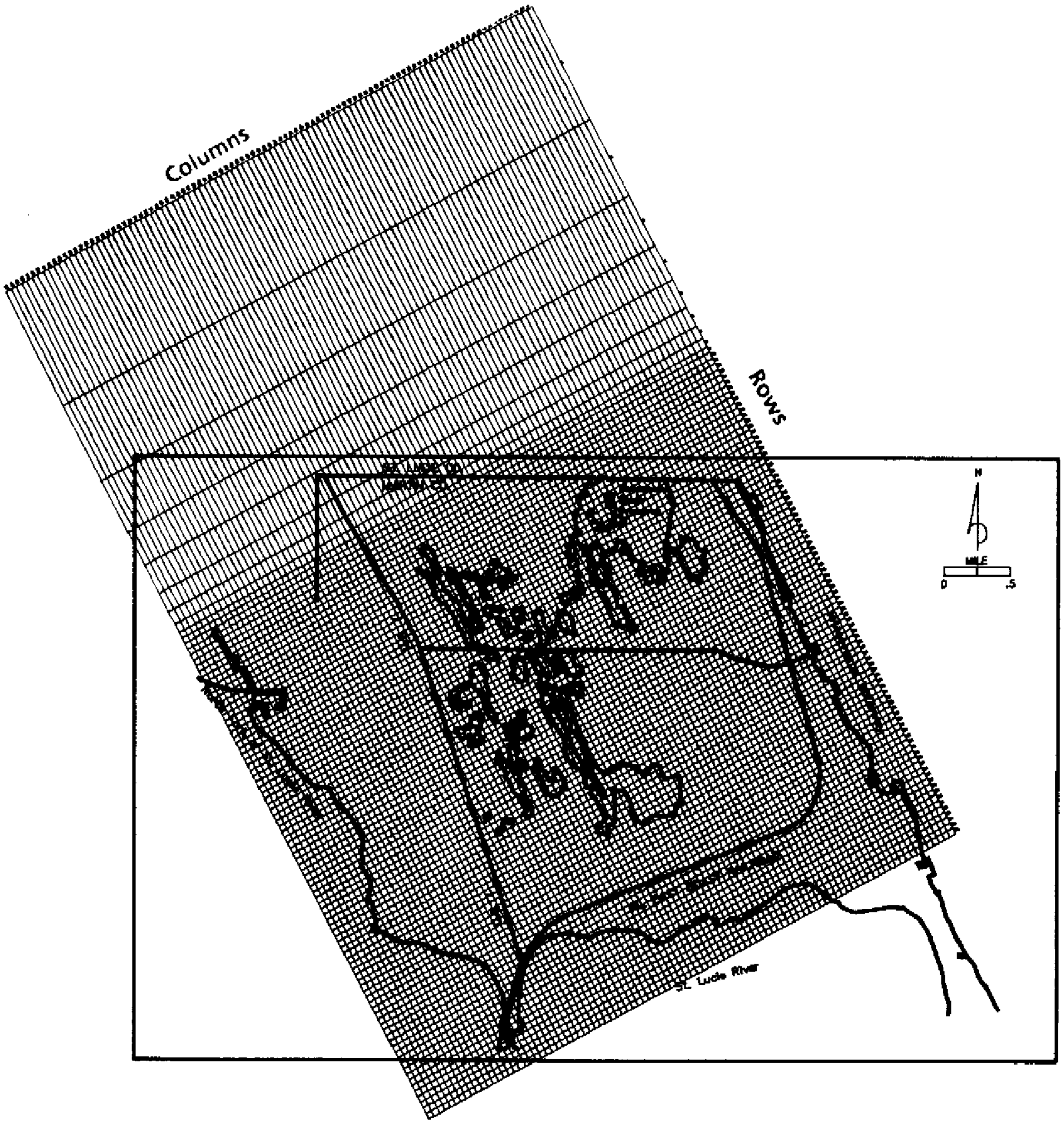

FIGURE 4. Dimensions and Orientation of Model Grid.

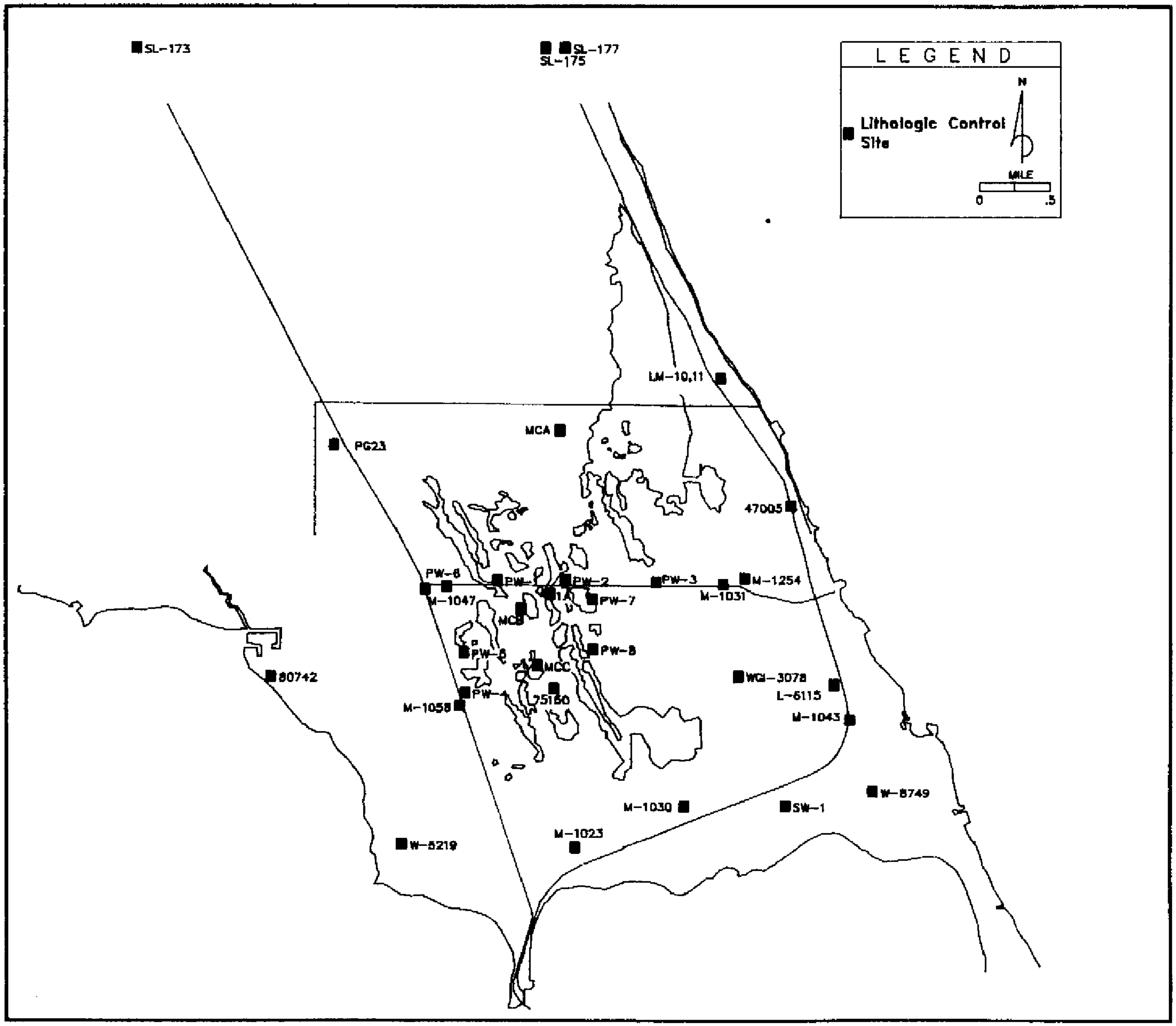

FIGURE 5. Location of Lithologic Control Sites.

calculated within a layer. In an unconfined layer transmissivity is continually recalculated as a product of hydraulic conductivity and the saturated thickness of the layer. Storage is determined from the specific yield. Under the confined/unconfined designation, it is assumed that the majority of the layer remains saturated throughout the simulation, so that it is not necessary to continually recalculate transmissivity. This layer type requires the input of both a specific yield and a storage coefficient, so that storage may alternate between confined and unconfined values.

It was originally intended that this model should consist of three layers, the bottom two layers being the producing zone and surficial sands as described above. The third layer would represent a thin sand layer overlying the other layers. The hardpan was to be the boundary between layers one and two. There were a couple of problems with this approach. First, although MODFLOW can simulate a wide variety of stresses on the ground water system, it has no explicit procedure for incorporating wetlands. When simulated as a separate layer, the model runs into severe numerical problems once the water table falls below land surface in response to stresses. Second, this three layer model was based on the notion of a continuous hardpan layer impeding vertical flow. However, data presented in Phase I of the JMM report indicated that this was not the case. Because of this, it was decided that including the hardpan as a continuous layer would be misrepresentative of the actual natural system.

HYDRAULIC PROPERTIES

An aquifer performance test (APT) was conducted on Production Well 7 (see Figure 4, "PW-7"), in the north Martin County Wellfield. A detailed account of this test was presented in Phase II of the JMM report (JMM, 1989).

Analysis of the APT placed the production zone transmissivity (T) at the site within the range of 17,000 to 22,000 gpd/ft. Based on a producing zone thickness of 90 feet at the APT site, a range of values as calculated for: hydraulic conductivity in the horizontal direction (k_h) (25 - 33 ft^2/day), and storage coefficient (S) (0.0002 - .0004). Repeated model runs at various S and T values showed water levels to be relatively insensitive to those parameters within the calculated range. Values of 30 ft/day and 0.0004 were used for the hydraulic conductivity and storage coefficient in layer two of the model.

Aquifer parameters reported by JMM at the APT site were consistent with those reported at other locations on the Jensen Beach peninsula. Therefore, it was assumed that the hydraulic properties of the aquifer did not vary significantly over the area of interest. A transmissivity value for each cell in layer two was input into the model as the product of the producing zone thickness in each cell and a constant k_h, derived from the APT. The use of this method assumes that the thickness of the producing zone remains saturated throughout the simulation period. A hydraulic conductivity of 23 ft/day was used for the surficial sands of layer one. This is consistent with literature values (Todd, 1980) for fine to coarse grained sand. Transmissivity within the top sand layer was continually recalculated by MODFLOW as the product of a constant k_h for layer one, and the fluctuating saturated thickness of the layer. Specific yield (S_y) values of 0.18 and 0.3 were chosen for layer one and layer 2, respectively. These values are within the range of representative values for sand reported by Driscoll (1986). Repeated calibration runs were used to verify these values. The leakance (Vcont) between layers one and two was calculated for each cell in the model grid as a function of vertical hydraulic conductivity (k_v) and layer thickness.

Little information is available on vertical hydraulic conductivity within the study area. Todd (1980) states that the anisotropy ratio for horizontal to vertical conductivity usually falls between 2 and 10 for alluvial deposits, but may range upwards of 100 if clay is present. A $k_{vertical}/k_{horizontal}$ anisotropy ratio of 1 to 10 was initially used for both layers of the model. Early model runs indicated that vertical conductance values calculated in this manner were too large, not accounting for vertical impedance to flow caused by fine sands and clay layers at the base of layer one. Repeated calibration runs suggested leakance values in the range from (0.005 - 0.013/day), approximately a quarter of those estimated, to be more realistic and closer to that calculated in phase II of the JMM report.

Values within this range were used in the final model.

RECHARGE

Recharge to the aquifer from precipitation was simulated using the recharge package in MODFLOW. The package specifies the amount of recharge applied to the highest active cell in the model. This recharge may be applied uniformly or in variable amounts throughout the model grid.

Daily precipitation data for the years 1987-89, collected from the rainfall station at the Martin County Utilities plant (centrally located within the study area) was used to calculate recharge. Not all of the rainfall which falls in an area becomes recharge to the aquifer. A portion of it is intercepted by impervious surfaces (buildings, roads, etc.) or plant life, and never reaches the ground. Of that portion of rainfall which reaches land surface, a portion will run off into ditches and canals and out to sea, part will be held at land surface in depressions until it evaporates, and another part will be held as storage in shallow soils. The fraction of annual rainfall which becomes recharge to the aquifer was represented in the model by multiplying rainfall by a percent recharge factor based on land use, slope, plant types, and depression storage (Restrepo, in press, Shine et al., 1989). Typical recharge factors used are listed below:

Land Use	Recharge Factor.
Forested	.70
Wetlands	
Mixed Forest	.65
Unforested	.55
Urban	
Low Density	.65
High Density	.50

Recharge was calculated using rainfall averaged over one month simulation periods. During the calibration period, it was found that these recharge factors worked well until the early part of 1989 when the area entered its second year of drought. During this time steep drops in water level were seen in monitoring wells across the peninsula, while simulated water levels remained at a higher level. This drop in actual water levels could only be accounted for by an additional loss of recharge. For equivalent rainfall events, less water is available for aquifer recharge during drought conditions due to the increased volume necessary for rewetting the dry soils. For this reason, an additional 10% loss of recharge was added for the calibration year 1989 to account for the effects of the long term drought.

EVAPOTRANSPIRATION

Loss of ground water due to evaporation, and transpiration from plant life was represented in the model by the evapotranspiration (ET) package. MODFLOW requires the input of a maximum ET rate. This rate is applied when the water table is at land surface and declines linearly to a designated extinction depth below which there is no further ET. For this model a modified ET package (Restrepo, in press) was used which represented the decline in the rate of ET as a non-linear function, and allowed for the designation of a capillary fringe zone.

This modified code was used to more accurately reflect the natural evapotranspiration process. Even if the water table is relatively deep, evapotranspiration will not necessarily go to zero because upward transport can still occur. Water can be drawn upward by capillary action from the water table into a zone in which the pores are saturated but the pressure is less than atmospheric. This zone is known as the capillary fringe. Within the capillary fringe moisture decreases gradually with height above the water table. The height to which the water will rise is a function of the grain size, shape, and lithology. Deep rooted plants may draw moisture from within the capillary fringe. The modified ET package includes this capillary fringe zone as a contributor of soil moisture. This model uses a capillary fringe thickness of one foot, which is within the range expected for medium grained sand.

Maximum ET rates in the model were based on pan evaporation from Vero Beach, and adjusted using stage data from a north Martin County wetland monitoring station (JMM, 1988). Monthly ET rates ranged from 2.5 to 6 inches. An extinction depth of five feet below land surface, based on root zone depths for indigenous vegetation and a one foot capillary fringe, was used throughout the modeled area. This falls within the range of root zone depths reported for south Florida (Restrepo, in press).

Sensitivity analysis, for a range of extinction depths, indicated that for smaller depths, little or no ET was removed from the model. At extinction depths greater than five feet, so much ET was removed that the model ceased to respond to any other stress.

BOUNDARY CONDITIONS

Only one type of boundary condition is used in this model:

Constant Head - Hydraulic head within the cell is input by the user and does not vary with time. Water may flow into or out of the cell, depending on the head gradient, but head within the cell does not change. Constant head boundaries occur where part of the boundary surface of the aquifer coincides with a surface of essentially constant head (e.g. the Intracoastal Waterway).

The Intracoastal Waterway, St. Lucie Inlet, and North Fork of the St. Lucie River are represented as constant head boundaries in both layers of the model. Water levels in the reaches of the St. Lucie Inlet are strongly influenced by the tides. Mean monthly high and low tide stages were available from SFWMD records for: the St. Lucie Inlet at Stuart (1973-1976), the Intracoastal Waterway at A1A bridge (9/82-3/84), the North Fork of the St. Lucie River at Sandpiper Bay (6/81-8/82), Britt Creek (5/82-8/82), and Kellstadt bridge (2/84-10/85). Because the period of record at each station was short, and represented a variety of time intervals, it was difficult to distinguish trends in mean monthly water levels. It was decided therefore, to use an average yearly value for each section of the coastline considered: 0.6 feet NGVD for the North Fork of the St. Lucie River, 0.9 feet NGVD for the Intracoastal waterway, and 0.3 feet NGVD for the St. Lucie Inlet. In order to test the validity of this decision, constant heads in the model were varied within a foot of the chosen value. Simulated water levels in coastal observation wells S1, S2, and S4 exhibited up to a half a foot of variability in response. Predicted water level values in all other observation wells, however, showed little sensitivity (less than 0.1 foot) to changes in constant head elevations within a foot of the yearly average.

A constant head boundary was placed at the coastline in layer one. All cells in this layer, from the coast to the edge of the grid, are designated as constant head. In layer two the aquifer was extended an additional two cell widths (480 ft) out from the coast to more closely simulate natural conditions, in which water in the deeper zone of the aquifer can flow under shallow bodies of water. The cells in layer two between the constant head boundary and the edge of the grid are inactive, or no flow cells. Figure 6 illustrates the arrangement of model boundaries.

Where the modeled area is not bordered by water, actual measured water levels were used to represent constant head boundaries in both layers. The grid spacing was expanded to the northwest so that a constant head boundary in the first cell would exert little influence within the actual area of interest.

DRAINS

The drain package simulates uni-directional flow from the aquifer to the drain. This flow occurs when simulated head in the aquifer rises above the bottom elevation of the drain. The rate of flow into the drain from any one cell (Q) is a function of the hydraulic conductance of the drain (C), and the difference between the hydraulic head in the cell (h) and the elevation of the bottom of the drain (d). Flow into the drain ceases when the water level drops below the elevation of the bottom of the drain. Howard Creek and drainage ditches near observation wells were represented in the model as drains. Drain bottom elevations ranged between 1.0 and 10.5 feet NGVD.

CALIBRATION

Ground water models are numerical approximations of natural aquifer systems. For this reason it is a questionable practice to use even a calibrated model as a predictor of exact water levels. Models are more correctly used to simulate trends in water level variations under various conditions.

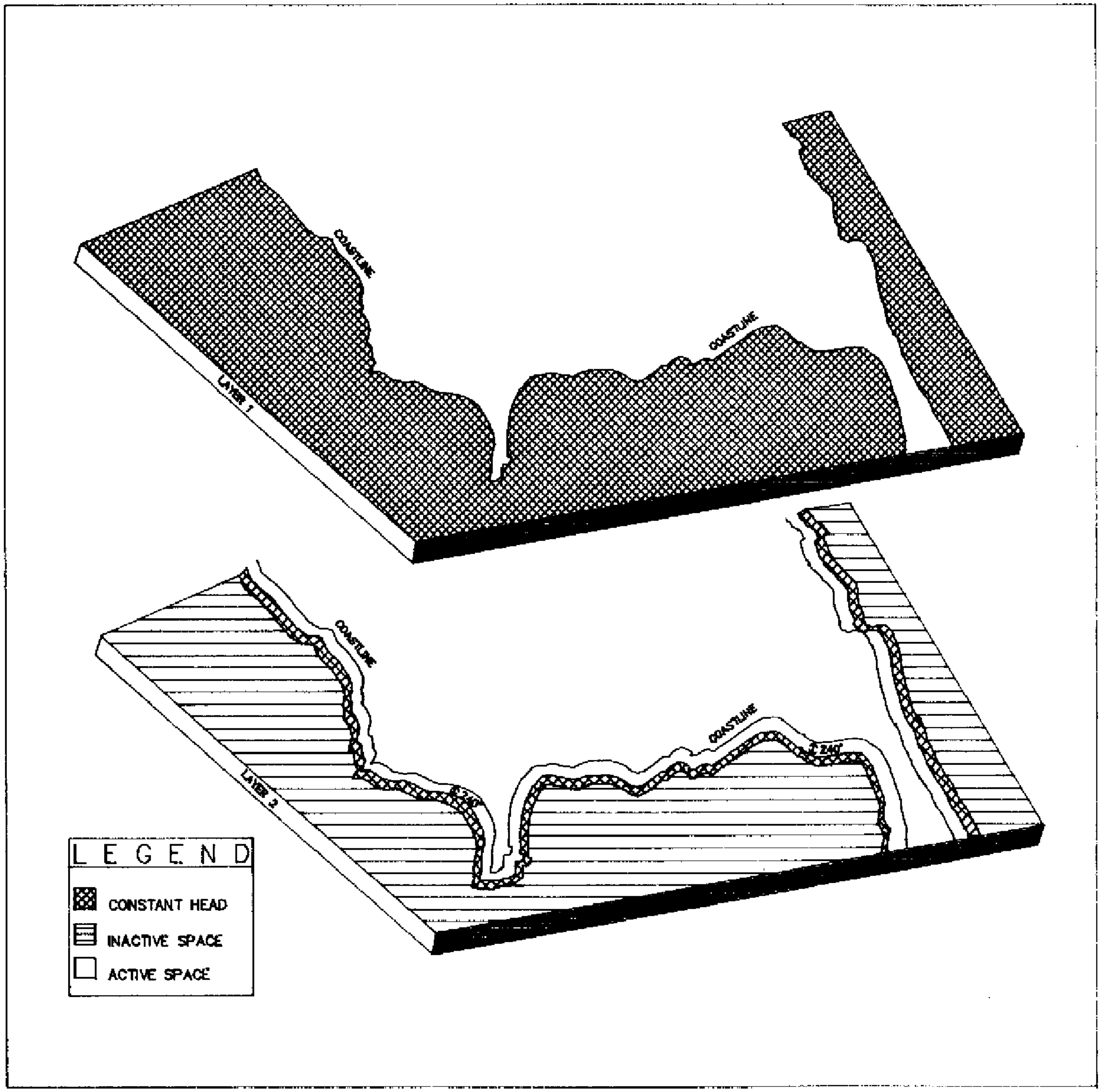

FIGURE 6. Arrangement of Model Boundaries.

When constructing a ground water model, an effort is made to simulate natural conditions as closely as possible. If measured values for aquifer transmissivity, storativity, hydraulic head, and all stresses were available at each nodal position within the model grid this would be a very straightforward matter. Unfortunately, the data base from which a model is developed is frequently very sparse, making it necessary to calibrate the model. This is accomplished by adjusting model parameters in areas where field data is unavailable, to yield accurate correlation between calculated and observed water levels.

This model was calibrated against historical records for the period of February 1987 through January 1989. Water levels from January 1987 were used for starting head values. Rainfall, evapotranspiration, and well field pumpage were varied monthly. Water use permits from the Martin County Utilities, Beacon 21, Pine Lake Village, Southern Estates and Jensen Park Estates were used as the basis for estimating the magnitude and location of ground water pumpage during the 35 month calibration period. Computed water levels were compared to actual measured levels in Martin County Utilities salt water intrusion monitoring network (Appendix I). Locations of the monitor wells are shown in Figure 2.

As seen in the graphs, the simulated water levels respond similarly to the measured ones, but are consistently higher. Simulated water levels are close to actual levels in the northern and coastal regions of the modeled area, but tend to run high in the central portion of the peninsula, about 1.5 feet higher on average. The exact causes of this condition are not known, but there are several possibilities. Due to lack of available data during the construction of the model, withdrawals from domestic self-supplied wells were not simulated. Actual water levels being consistently higher than modeled levels could be a reflection of these withdrawals. Another possibility would be the existence of downward leakance from layer two that was not represented in the model. Other adjustments could be made that would lower predicted levels (e.g., increasing the magnitude of ET and/or decreasing the amount of recharge), but not without losing the seasonal water level trend or making unreasonable assumptions about the natural system.

RESULTS AND DISCUSSION

1. Is there any validity to the concern over the effects of hardpan perforating activities on adjacent wetland areas ? Can it be quantified?

This question is really asking whether or not the hardpan has a protective effect on water levels in an overlying wetland, and if so, whether it can be measured. To answer this question it is necessary to provide some background information on the wetlands, and the hardpan itself.

The wetlands in the vicinity of the north Martin County Wellfield are depressional features, elongate in a direction parallel to the coast. They were most likely formed by wind scour on the inland side of migrating dunes or a barrier beach. Wetland formation of this type is common near the coast, where shallow water table conditions provide an adequate water supply (Mitsch et al., 1986).

Because they are small in size, usually less than two acres, and have been assumed to be perched, there has been a tendency to think of these wetlands as isolated entities rather than elements of a larger hydrogeologic system. Wetlands, however, may play a significant role in the hydrogeology of a basin. They can modify the character of runoff, influence discharge/recharge relationships with the underlying aquifer, and affect the potential for ground water development (O'Brien and Motts, 1980).

The actual significance of the wetlands on the Jensen Beach peninsula will only be apparent when considered in relation to the underlying aquifer. The first step in understanding the relationship between wetland and wellfield is determining whether or not the wetlands are truly perched.

A low permeability, or hardpan layer, is found at depths of two to four feet in the vicinity of the wellfield. Hardpan is composed of sand cemented by humus (the decomposition product of organic matter which becomes the organic portion of soil). Hardpan soils are ground water podzol, or spodosol (Davis, 1946). Spodosols are defined simply as soils having a spodic horizon, which is an illuvial subsurface where amorphous materials composed of organic matter, iron and aluminum oxides have accumulated. The thickness and continuity of the spodic horizon are believed to be controlled by the height of a fluctuating water table, pH changes, and changes in particle size distributions (Collins, M.E., Personal Communication May 1990). It is this spodic horizon which is commonly known as hardpan.

As stated in the section on model discretization, the hardpan is not a continuous uniform layer. It varies greatly in thickness over short distances, dipping, thinning and disappearing all within the same wetland. This variable nature was noted by McCollum and Cruz (1981), and confirmed by test holes drilled during Phase I of the present study (JMM, 1988). Thus while less permeable layers are present in the wellfield area, the wetlands cannot be considered perched in the classical sense of the word as they are hydraulically connected to the rest of the aquifer.

The leaky nature of the hardpan layer is supported by daily water level data collected from monitoring well cluster MCC (see Figure 2). The data indicates that water level changes in the sand unit below the hardpan take place within two to three days of a rainfall event. Conversely, if water levels are drawn down in the sand layer below the hardpan, the water levels above the hardpan will be impacted. This is caused by the creation of a downward flow gradient across the hardpan layer resulting from the drawdown caused by a wellfield in the sand layer below the hardpan. This situation causes the wetland to drain more rapidly in dry times. If the hardpan layer around a given wetland is continuous, the effect of the lower water levels below the hardpan layer may be seen in the wetland as a reduction of the depth of inundation, a change in the hydroperiod, or both. When the water level in the sand layer below the hardpan is high, the downward flow gradient across the hardpan does not exist. This results in reduced infiltration rates, which in turn cause the wetland to drain more slowly.

Since the hardpan layer is leaky, it would be convenient to say that the rules prohibiting piercing the hardpan are without merit. This is not the case. Figure 7 illustrates the occurrence of vertical flow around discontinuous leaky layers. The presence of low permeability layers within a higher permeability unit can lead to the development of a lens of saturated material surrounded by unsaturated conditions. The presence of a perched water table above the hardpan has been documented at numerous locations on the Jensen Beach peninsula. Conditions of this type, however, are both spatially and temporally discontinuous. While heavy rainfall may lead to the formation of a saturated zone underlain by unsaturated conditions, this type of zone will tend to dissipate through time under the influence of evapotranspiration and downward percolation. As seen in Figure 7, increasing the number or size of holes in a restrictive layer may lead to an increased rate of downward percolation.

Determining whether or not an individual wetland will be affected by a hardpan perforating lake requires a knowledge of the condition of the hardpan layer in the vicinity of that wetland. If the hardpan is fairly continuous between a wetland and a proposed lake, a greater setback distance may be required to reduce wetland impacts due to the increased component of horizontal flow induced by a restrictive layer (Figures 8 and 9).

The concern over the effects of hardpan perforating activities on adjacent wetland areas is a valid one. The extent to which this concern is warranted will vary from place to place, depending on the extent and geometry of the hardpan layer in and around an individual wetland. A practical way to quantify these parameters is to map a continuous soil profile between the wetland area in question, and the area of proposed construction. This has been done in other areas using ground penetrating radar or other subsurface geophysical techniques. It is possible these methods may be applicable to the study area.

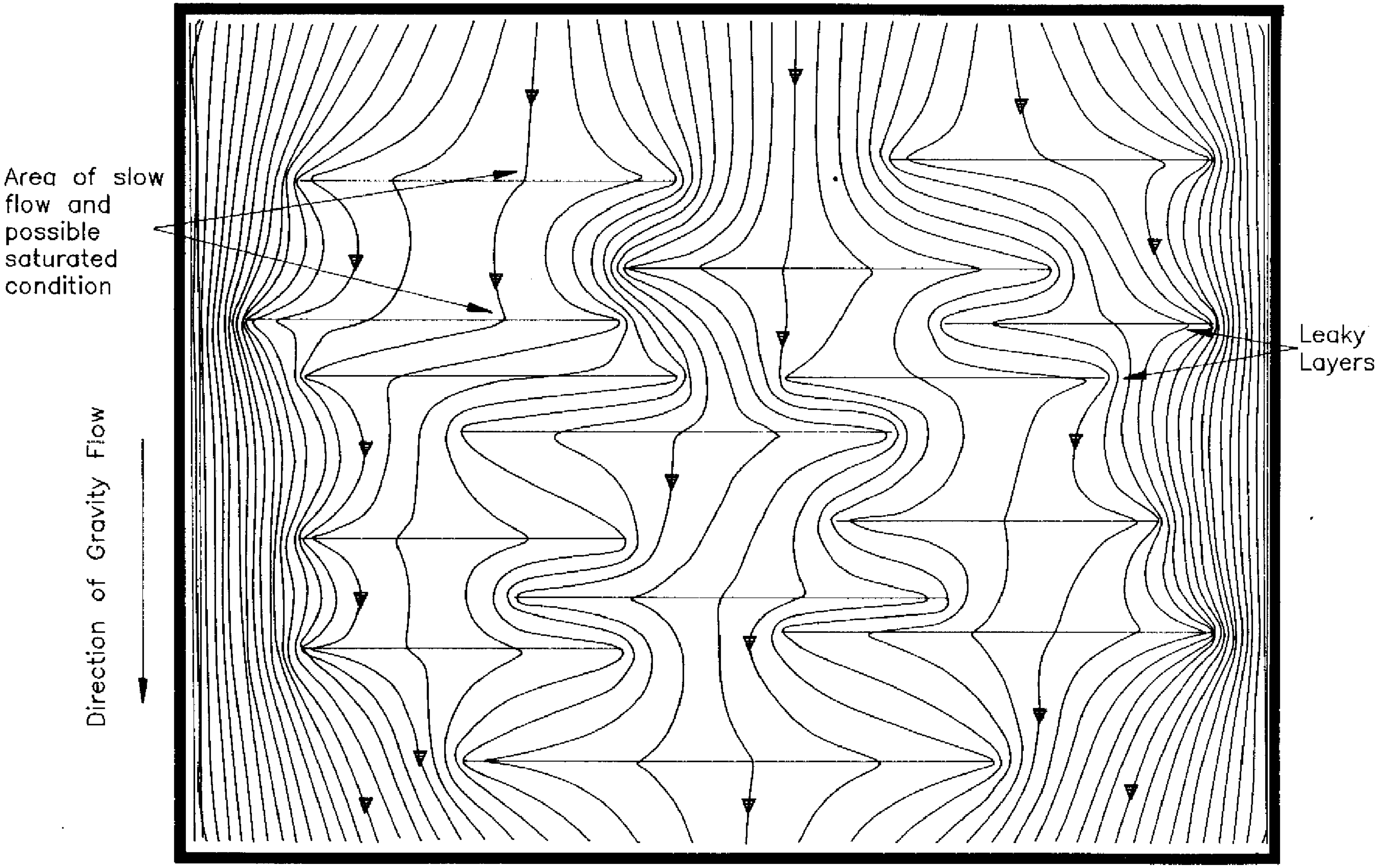

FIGURE 7. Conceptual Drawing of Gravity Flow Between Thin Leaky Layers (After Strack, 1989).

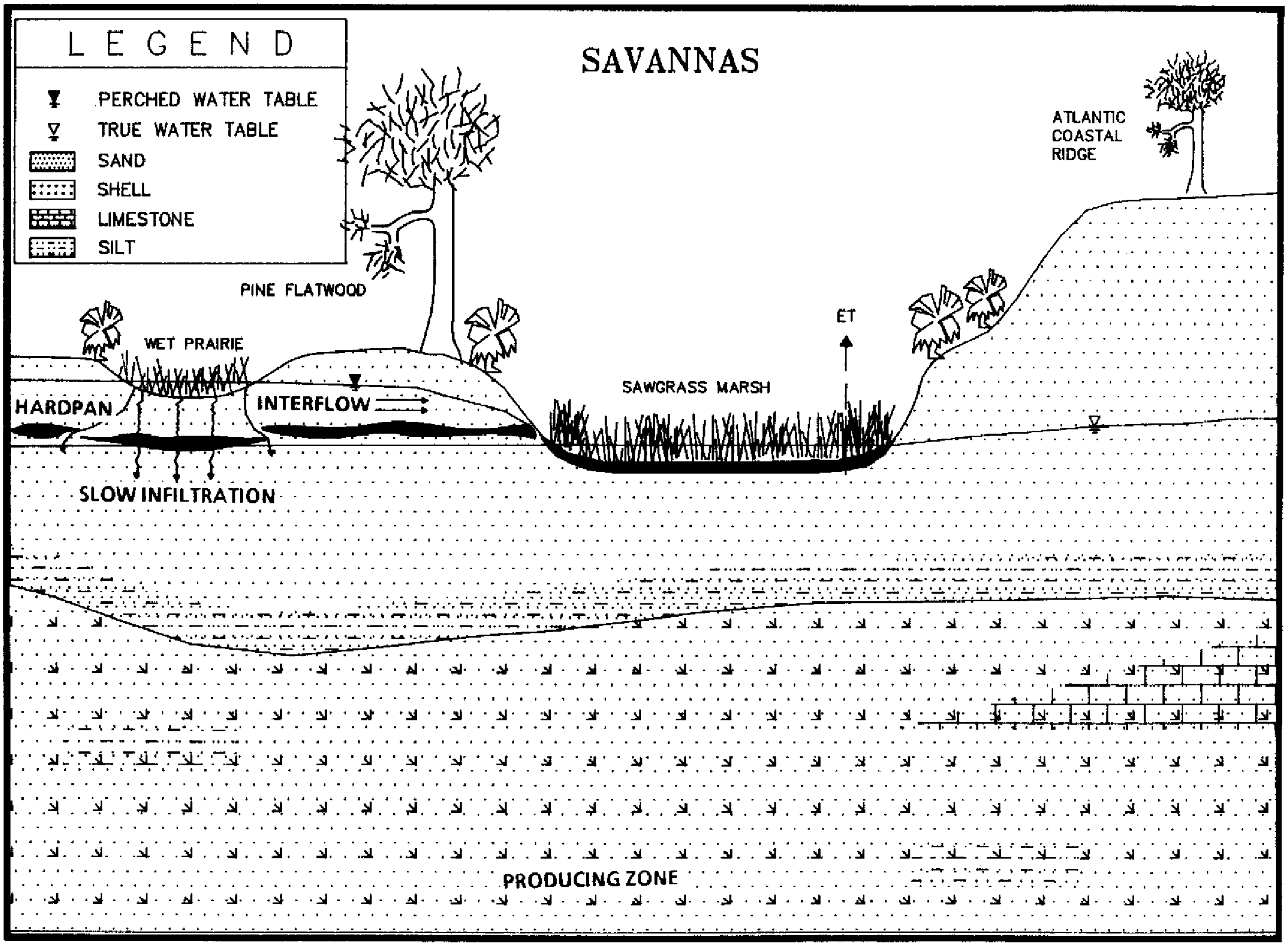

FIGURE 8. Horizontal and Vertical Flow in the Presence of a Restrictive Hardpan Layer Without the Addition of a Producing Well.

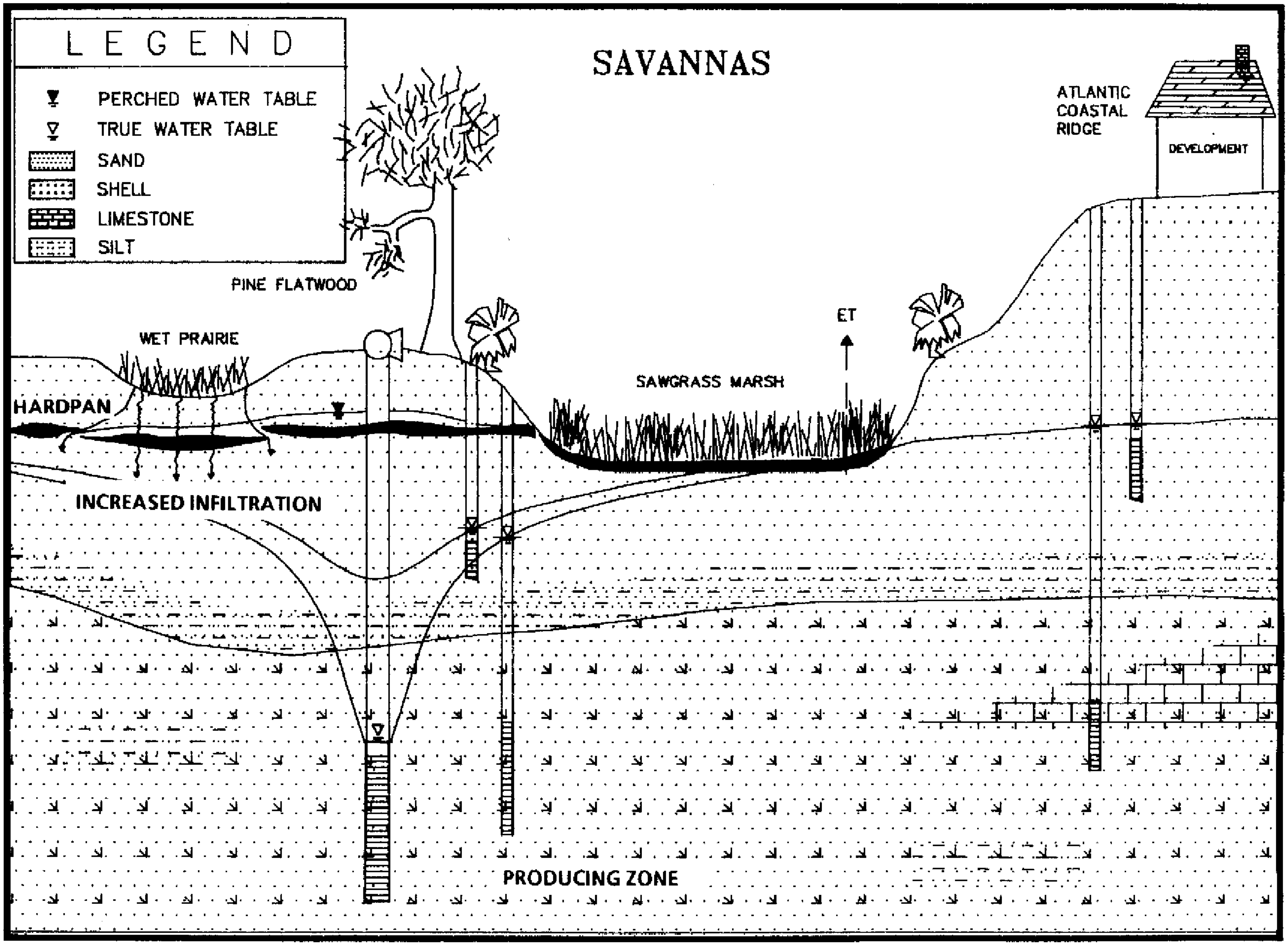

FIGURE 9. Horizontal and Vertical Flow in the Presence of a Restrictive Hardpan Layer with the Addition of a Producing Well.

2. Is the existing operational strategy of the NMCW optimum? How might it be modified in order to minimize wetland impacts?

The District's wellfield optimization model, MODMAN, was used to address these questions. MODMAN is a wellfield optimization routine developed by GeoTrans, Inc. for the SFWMD, which is linked to MODFLOW. It uses the response matrix technique to transform a ground water management problem into a linear or mixed-integer program. Used in conjunction with optimization software, and a calibrated MODFLOW model, MODMAN yields optimal answers to water management problems based on a series of explicitly stated constraints. Typically, the MODMAN code is used to address the following questions: 1) where should pumping and injection wells be located, and 2) at what rate should water be extracted or injected from each well? The optimal solution minimizes or maximizes a user defined function while satisfying all user defined constraints (GeoTrans, 1990).

The validity and accuracy of management solutions is intimately tied to the validity and accuracy of the MODFLOW model. Ground water modeling is based on many approximations. For example, hydrogeologic parameters are often estimated from field measurements, and then extrapolated to areas where no information exists. Output from the MODFLOW Model and MODMAN optimization module are only as accurate as the estimated data used to construct the model. Therefore, optimized pumping rates should be viewed as general in nature.

The problem of wellfield optimization was addressed from two different directions. First it was necessary to determine whether pumpage from the wellfield could be optimized to meet the SFWMD guideline of less than one foot of wellfield induced drawdown under wetland areas, while pumping at the current allocation of 2.5 mgd. MODMAN was configured to minimize the maximum drawdown under wetland areas while maintaining a withdrawal rate of 2.5 mgd, during a 90 day no rain simulation. Table 2 shows the minimum possible drawdowns under wetland areas for each week of the 90 day simulation. The one foot guideline is exceeded at three wetland control locations after only two dry weeks (5, 7 and 8 in Figure 10). By the end of the 12th week of drought, all but one of the wetland control sites (#10) were experiencing greater than two feet of modeled drawdown.

Having established that the SFWMD guideline for minimizing wetland impacts can not be met if the utility continues to pump at its current allocation, the problem was attacked from the opposite direction by determining what quantity of water could be withdrawn without violating the one foot drawdown guideline. MODMAN was configured to maximize the pumpage from the wellfield while allowing no more than one foot of drawdown under wetland areas for the 90 day drought described above, and for a 90 day period with average dry season rainfall. The same simulations were then run with a 0.5 foot, rather than a 1.0 foot, drawdown constraint under wetland areas. The results of these four simulations, reported in terms of optimum pumping rate from each existing well, are given in Table 3.

For all simulations, the majority of pumpage was concentrated in wells six and nine. Conversely, very little water was available from production wells five, seven and ten. The rest of the wells (1,2,3,4,8) were pumped at rates well below their production capacity. Table 4 lists the wellfield withdrawal rates for each week of the four simulations. Based on these simulations, it is conservatively estimated that with proper optimization, the north Martin County Wellfield (in its existing configuration) should be able to withdraw at least 1 mgd on average from the Surficial Aquifer System without violating current guidelines for wetland protection during a 90 day no rainfall situation.

For these simulations, drawdown restrictions were placed only under wetland areas. If restrictions were imposed beneath surface water management lakes as well, the rate of flow from production well nine would probably be severely cut back. The utility is presently permitted to pump 2.5 million gallons of water per day. This quantity is significantly larger than that which can be withdrawn from the wellfield without impacting adjacent wetland areas.

TABLE 2: OPTIMIZED DRAWDOWNS AT ELEVEN WETLAND LOCATIONS FOR A 90 DAY NO RAIN SIMULATION AT THE CURRENT ALLOCATION OF 2.5 MGD.

WETLAND CONTROL SITE NUMBER	Week #											
	1	2	3	4	5	6	7	8	9	10	11	12
1	.14	.29	.43	.58	.16	.28	.43	.57	.71	1.45	2.07	2.38
2	.01	.03	.05	.08	.23	.42	.67	.85	1.02	1.72	2.31	2.61
3	.01	.03	.06	.10	.86	1.68	2.52	2.62	2.63	2.63	2.62	2.62
4	.04	.09	.15	.22	2.28	2.57	2.62	2.62	2.62	2.62	2.63	2.63
5	.64	1.17	1.60	1.97	.44	.57	.83	1.58	2.48	2.61	2.61	2.61
6	.05	0.12	.20	.29	1.91	1.81	1.7	1.68	1.66	1.67	2.11	2.60
7	.58	1.12	1.61	2.03	2.42	2.61	2.62	2.62	2.56	2.62	2.53	2.61
8	.61	1.18	1.71	2.18	1.33	1.55	1.75	1.94	2.12	2.29	2.45	2.61
9	.29	.58	.85	1.10	.42	.54	.65	.77	.89	1.00	1.12	1.24
10	.06	.14	.23	.32	.07	.09	.12	.16	.19	.23	.27	.31
11	.01	.02	.03	.86	1.04	1.30	1.57	1.84	2.10	2.36	2.60	2.72

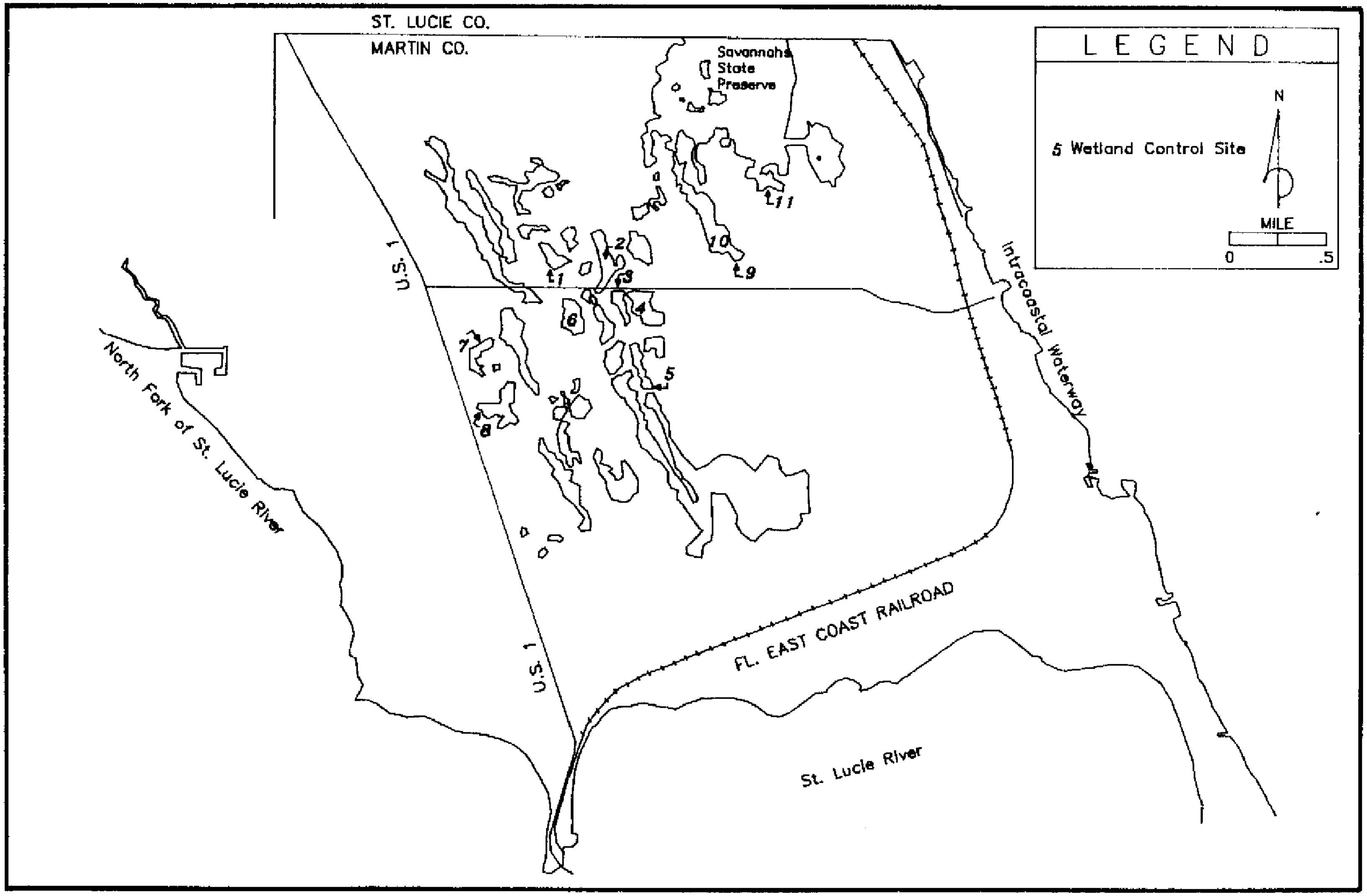

FIGURE 10. Location of Wetland Control Sites.

TABLE 3: RESULTS OF MODMAN SIMULATIONS FOR OPTIMIZATION OF WELLFIELD OPERATIONAL STRATEGY SHOWING OPTIMAL PUMPING RATE AT EACH PRODUCTION WELL IN UNITS OF GALLONS PER MINUTE (GPM)

I. 90 days no rainfall, 1' drawdown constraint under wetland areas.

Week #	PW-1	PW-2	PW-3	PW-4	PW-5	PW-6	PW-7	PW-8	PW-9	PW-10
1	130	0	280	220	290	280	0	284	249	0
2	274	0	280	172	141	280	130	206	250	0
3	274	119	280	0	115	280	120	71	250	223
4	215	155	173	31	36	280	0	68	250	0
5	0	28	51	32	35	280	25	63	250	0
6	26	28	59	33	29	280	0	58	250	0
7	28	25	59	33	0	280	0	54	250	0
8	26	0	55	33	0	280	0	50	250	0
9	0	0	50	35	0	280	0	47	250	0
10	0	0	45	35	0	280	0	44	250	0
11	0	0	40	34	0	280	0	41	250	0
12	37	0	35	33	0	280	0	39	250	0

II. 90 days no rainfall, 0.5' drawdown constraint under wetland areas.

Week #	PW-1	PW-2	PW-3	PW-4	PW-5	PW-6	PW-7	PW-8	PW-9	PW-10
1	274	104	280	220	0	280	107	218	250	0
2	132	52	198	63	0	280	0	35	250	102
3	0	0	13	32	0	280	0	35	250	0
4	0	0	24	34	0	280	0	32	250	0
5	0	0	25	32	0	280	0	30	250	0
6	0	0	23	29	0	280	0	27	250	0
7	0	0	0	25	0	280	0	25	250	0
8	0	0	0	0	0	280	0	0	250	0
9	0	0	0	0	0	280	0	0	250	0
10	0	0	0	0	0	280	0	0	250	0
11	0	0	0	0	0	280	0	0	250	0
12	0	0	0	74	0	280	0	0	250	0

TABLE 3: (CONTINUED)

III. 90 days average Nov-Jan rainfall, 1' drawdown constraint under wetland areas.

Week #	PW-1	PW-2	PW-3	PW-4	PW-5	PW-6	PW-7	PW-8	PW-9	PW-10
1	134	0	280	220	0	280	279	284	250	0
2	274	0	280	220	0	280	87	270	250	66
3	274	0	280	220	0	280	82	120	250	228
4	274	194	280	74	236	280	46	115	250	40
5	274	120	280	14	290	280	44	112	250	32
6	122	63	161	70	84	280	46	112	250	39
7	133	62	161	68	89	280	44	109	250	38
8	135	61	160	69	88	280	43	108	250	37
9	136	61	158	68	88	280	42	106	250	35
10	133	59	153	67	85	280	41	103	250	34
11	130	58	150	67	82	280	41	103	250	33
12	128	57	148	67	80	280	41	102	250	32

IV. 90 days with average Nov-Jan rainfall, 0.5' drawdown constraint under wetland areas.

Week #	PW-1	PW-2	PW-3	PW-4	PW-5	PW-6	PW-7	PW-8	PW-9	PW-10
1	259	0	280	220	0	280	136	242	249	67
2	274	153	280	23	269	280	0	59	249	65
3	49	31	78	33	38	280	0	59	249	0
4	57	32	73	33	43	280	0	56	249	0
5	60	31	76	35	40	280	0	56	249	0
6	65	31	78	36	40	280	0	55	249	0
7	63	30	75	36	38	280	0	54	249	0
8	61	30	72	37	35	280	0	53	249	0
9	58	29	69	36	33	280	0	52	249	0
10	55	28	65	36	31	280	0	51	249	0
11	55	28	64	36	29	280	0	51	249	0
12	55	28	63	36	29	280	0	51	249	0

TABLE 4: MODELED PREDICTIONS FOR WATER AVAILABILITY (IN MILLION GALLONS PER DAY) FROM THE NORTH MARTIN COUNTY WELLFIELD DURING DROUGHT (90 DAYS NO RAINFALL) AND WET (AVERAGE NOV - JAN. RAINFALL) CLIMACTIC CONDITIONS, AND DIFFERENT DRAWDOWN CONSTRAINTS.

Week #	Drought[1]	Drought[2]	Wet[1]	Wet[2]
1	2.49552	2.49408	2.49408	2.49552
2	2.49408	1.59984	2.49408	2.40768
3	2.49264	0.87696	2.49552	1.24704
4	1.73808	0.89136	2.57472	1.24848
5	1.09872	0.88704	2.4408	1.25136
6	1.09728	0.87552	1.76544	1.25856
7	1.04832	0.83376	1.77552	1.2456
8	0.99792	0.76176	1.7712	1.2312
9	0.95184	0.76176	1.76112	1.21392
10	0.94032	0.76176	1.73376	1.1952
11	0.92736	0.76176	1.71792	1.19088
12	0.96912	0.86832	1.70496	1.18944
Mean	1.4376	1.03116	2.06076	1.43124

[1] One foot drawdown constraint placed under wetland areas
[2] 0.5 foot drawdown constraint placed under wetland areas

While this report was in review an opportunity presented itself to test the applicability of using the model as a tool for wellfield optimization. In September 1990, concern arose over the effect of the north Martin County Wellfield on water levels in the nearby Savannas. It was decided by the Regulation Department of SFWMD that one foot of drawdown under the southern end of the Savannas may not be an acceptable impact. MODMAN was configured to allow no more than 0.2 feet of drawdown at control sites nine and ten. No constraints were placed on drawdowns under the small wetland areas in and around the wellfield. Results of the MODMAN simulations indicated wells 2, 3, and 7 to be the primary causes of drawdown under the Savannas.

In compliance with limiting condition #29 of their water use permit, Martin County Utilities submitted a wellfield operating plan which would limit drawdowns in this area by placing wells 2, 3, and 7 into standby status. Those wells on standby would be restricted to 96 hours of pumping per month, as opposed to 720 hours per month during unrestricted operation. Computer analysis of the proposed operating plan indicated no drawdown under the Savannas as a result of the seven unregulated wells and no more than 0.2 ft of drawdown as a result of wells 2, 3, and 7. The new operating schedule was implemented on October 5, 1990.

Field data was used to corroborate modeling predictions. Water levels rises of up to 5 feet were noted across the peninsula in response to heavy rains near the end of September, but by November 6, following a dry October, water levels were again on the decline, with the exception of the area affected by the new wellfield operating plan. Monitoring wells W6A,B and W5A, the nearest to the Savannas (see Figure 2), and no longer impacted by the wellfield, experienced no noticeable decline in water levels.

The operational strategy of the north Martin County Wellfield can be optimized to minimize wetland impacts. It can not, however, be optimized to meet the one foot drawdown guideline at the current permitted allocation of 2.5 mgd. Assuming that wetland protection takes precedence over aesthetic protection of development lakes, wellfield operation may best be modified by eliminating pumpage from wells 7 and 10, and placing the rest of the wellfield on a rotational schedule that would concentrate withdrawals around wells 6 and 9.

3. Is the current well configuration of the NMCW optimum, or can it be modified to minimize effects on wetlands or residential lakes?

Most of the ten existing production wells of the north Martin County wellfield are located within a few hundred feet of one of the small wet prairies which dot the interior of the peninsula. Figures 11 and 12 show the extent of the steady-state cone of depression for the wellfield under average rainfall and drought conditions at the present permitted allocation of 2.5 million gallons per day. Even during a year of normal rainfall as much as four feet of drawdown can be expected under some wetland areas. The SFWMD guidelines presently allow less than one foot of pumpage induced drawdown under a wetland area, but even this guideline is not a guarantee against adverse impacts. The only solution to this problem is to reduce pumpage from the wellfield. Before this is possible a suitable alternative source of water is required.

Buildout demand for the north county area was estimated at 11.6 million gallons per day (Nealon et al., 1987), substantially larger than the present allocation of 2.5 million gallons per day. The need for expanding withdrawal capacity must be considered when exploring alternative sources.

Three possibilities were examined as additional water sources for north Martin County: 1) construction of additional surficial wells on the peninsula proper, 2) construction of additional surficial wells west of the North Fork of the St. Lucie River, and 3) desalination of Floridan Aquifer System water.

Construction of additional Surficial Aquifer System wells on the Jensen Beach peninsula to meet buildout demands may not be a viable option due to expected impacts to existing users, continued wetland impacts, and the possibility of saltwater intrusion. To protect wetlands on the peninsula, the pumpage from the existing public utility wells must be reduced. If new Surficial Aquifer System wells are

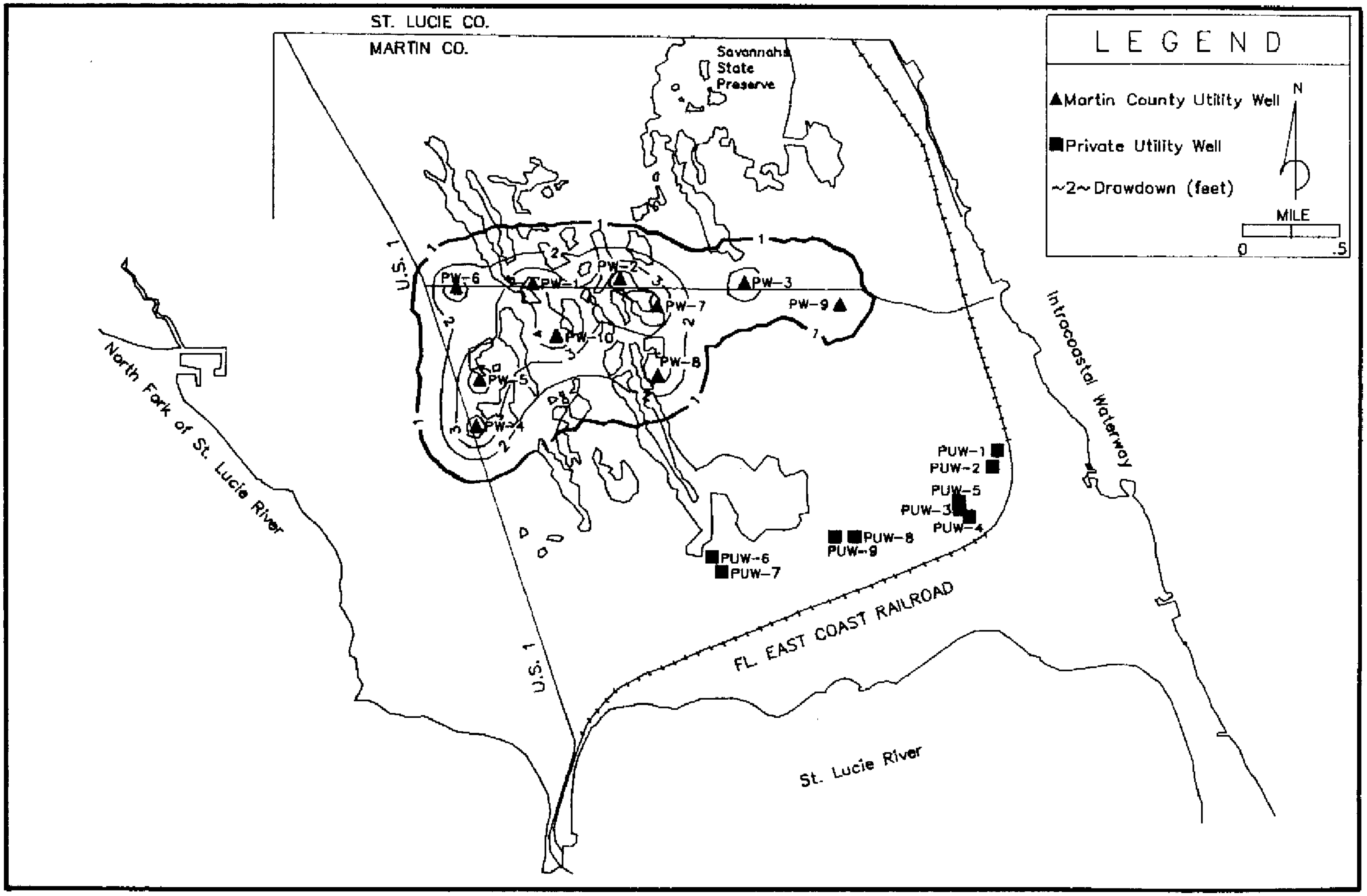

FIGURE 11. **Steady-State Cone of Influence for the NMCW Under Average Rainfall Conditions, When the Wellfield is Pumping its Maximum Allocation.**

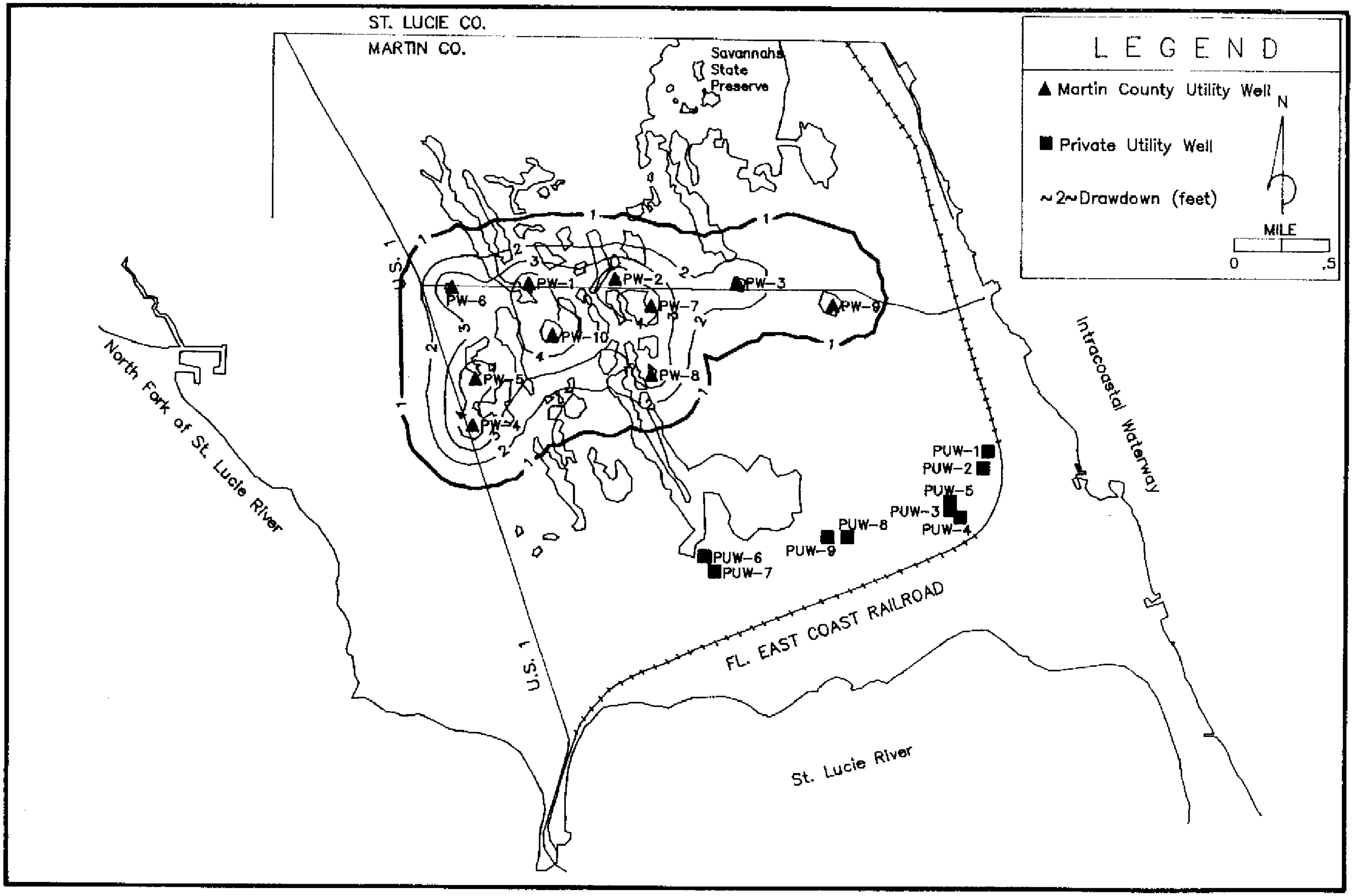

FIGURE 12. Steady-State Cone of Influence for the NMCW Under 1989 Drought Conditions, When the Wellfield is Pumping its Maximum Allocation.

constructed, they would have to be constructed away from wetland areas to prevent impacts. This would require placing them nearer to the coast, since the small wetland areas are ubiquitous throughout the interior of the peninsula. Lithologic descriptions from the peninsula indicate that the aquifer thickens to the east and south, becoming more productive near the coast. Unfortunately, these areas are already highly developed, presenting a number of difficulties when attempting to site new well locations.

The southeast corner of the peninsula is not covered by Martin County Utilities service area. It has several major existing Surficial Aquifer System users (those holding individual water use permits from the SFWMD). Figure 13 shows the steady-state cone of influence of these private wells, from Southern Estates Utilities, Pine Lake Village, Jensen Park Estates, and the former Beacon 21 development, under 1989 drought conditions, when they are pumping their permitted allocations. Additional Surficial Aquifer System wells would have to be situated so as to avoid impacting these existing users. An added difficulty in placing major producing wells in developed areas is the increase in the number of complaints over drawdowns in development lakes, and the detrimental effects on individual home irrigation wells. These effects include lower water levels in wells and some instances of well failure.

Locating new wells near the coastal reaches of the peninsula could lead to problems of water quality. The east coast and southwest corner of the peninsula are areas of septic tank use, presenting potential wellfield protection problems (Nealon et al., 1987). In addition, there is the potential for saltwater intrusion as the cone of depression expands near the coast. Assuming it is possible to overcome the difficulties associated with locating new production wells away from the interior of the peninsula, the question remains as to whether there is sufficient storage in the Surficial Aquifer System to meet the needs of the increasing population.

The specific capacity of a well is defined as the discharge rate per unit drawdown, commonly expressed as gallons per minute per foot of drawdown (Driscoll, 1986). It is determined in the field by measuring drawdown in a well at a variety of discharge rates. It can also be simulated using MODFLOW. Pumpage from a single well was simulated under steady-state conditions at six discharge rates, beginning with 100 gpm, and increasing in steps of 100 to 600 gpm. The model calculated the maximum drawdown at each of these rate steps. Figure 14 illustrates the decrease in specific capacity with increasing drawdown. Significant declines in the specific capacity of a well can be attributed to either decreasing transmissivity due to a reduction in the saturated thickness of the aquifer or an increase in well loss associated with clogging or deterioration of the well screen (Todd, 1980). Since simulated wells neither clog nor deteriorate, the loss of productivity seen here is attributable to dewatering of the aquifer. The results of the simulated step-drawdown test are plotted in Figure 15. This graph shows the results of two separate tests, the first beginning at 100 gpm and stepping up to 300 gpm (line I), and the second at 300 gpm stepping up to 600 gpm (line II). Steeper slopes and smaller y intercepts indicate larger head loss. It is apparent from Figure 15 that the simulated well experiences a sharp increase in head loss at pumping rates of more than 300 gpm per well. After this point there is a sharp decrease in the additional yield which can be obtained for each additional foot of drawdown, leading to increased inefficiency. The present wellfield, pumping at the rate of 300 gpm in each of its ten wells, could produce as much as 4.32 million gallons of water per day. To meet the predicted buildout demand of 11.6 mgd for the service area, an additional 27 wells pumping at 300 gpm would be required. Figure 16 depicts the expansion of the one foot cone of influence of the existing wellfield with increasing pumping rates. This simulation was run to steady-state conditions using average yearly rainfall with all wells pumping at equal rates. Judging by the extent of the cone of influence of the present wellfield a rate of 300 gpm (4.32 mgd), it is unlikely that the Surficial Aquifer System on the Jensen Beach peninsula can support the projected water demand at buildout without inducing salt water intrusion. Regardless of wetland impacts and effects on other users, there is not sufficient storage within the Surficial Aquifer System to keep up with increasing demand.

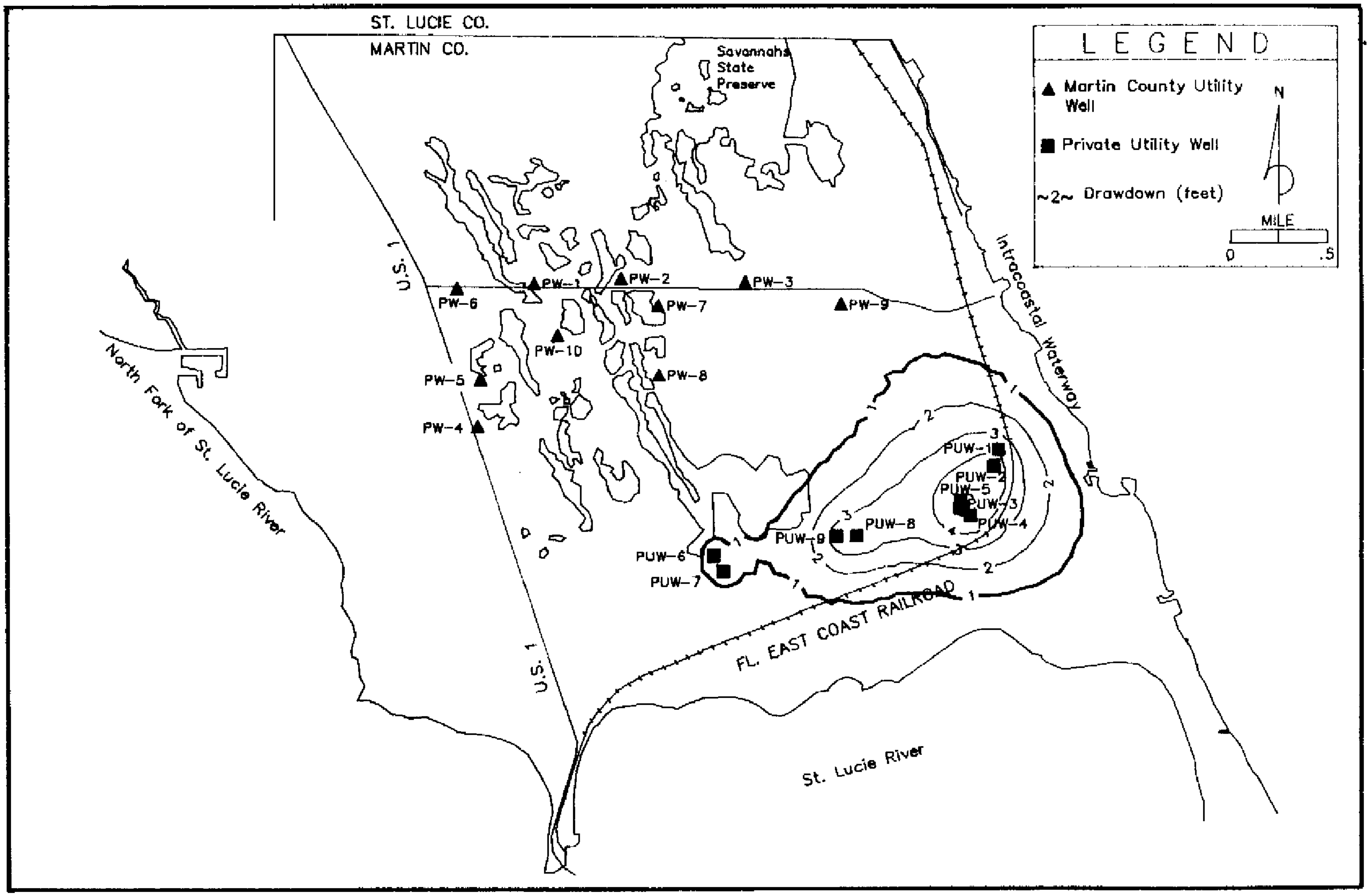

FIGURE 13. Steady-State Cone of Influence of Major Private Utilities Under 1989 Drought Conditions, When all are Pumping their Maximum Allocations.

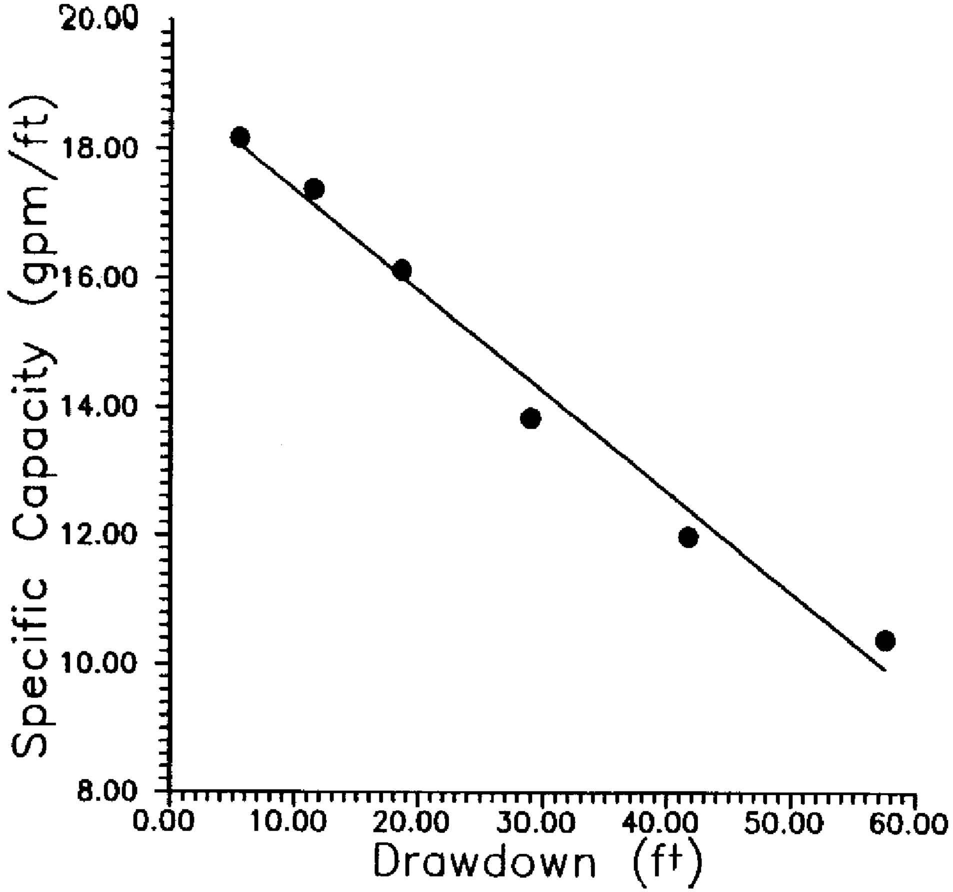

FIGURE 14. Relationship Between Specific Capacity and Drawdown, as Derived from Model Simulations.

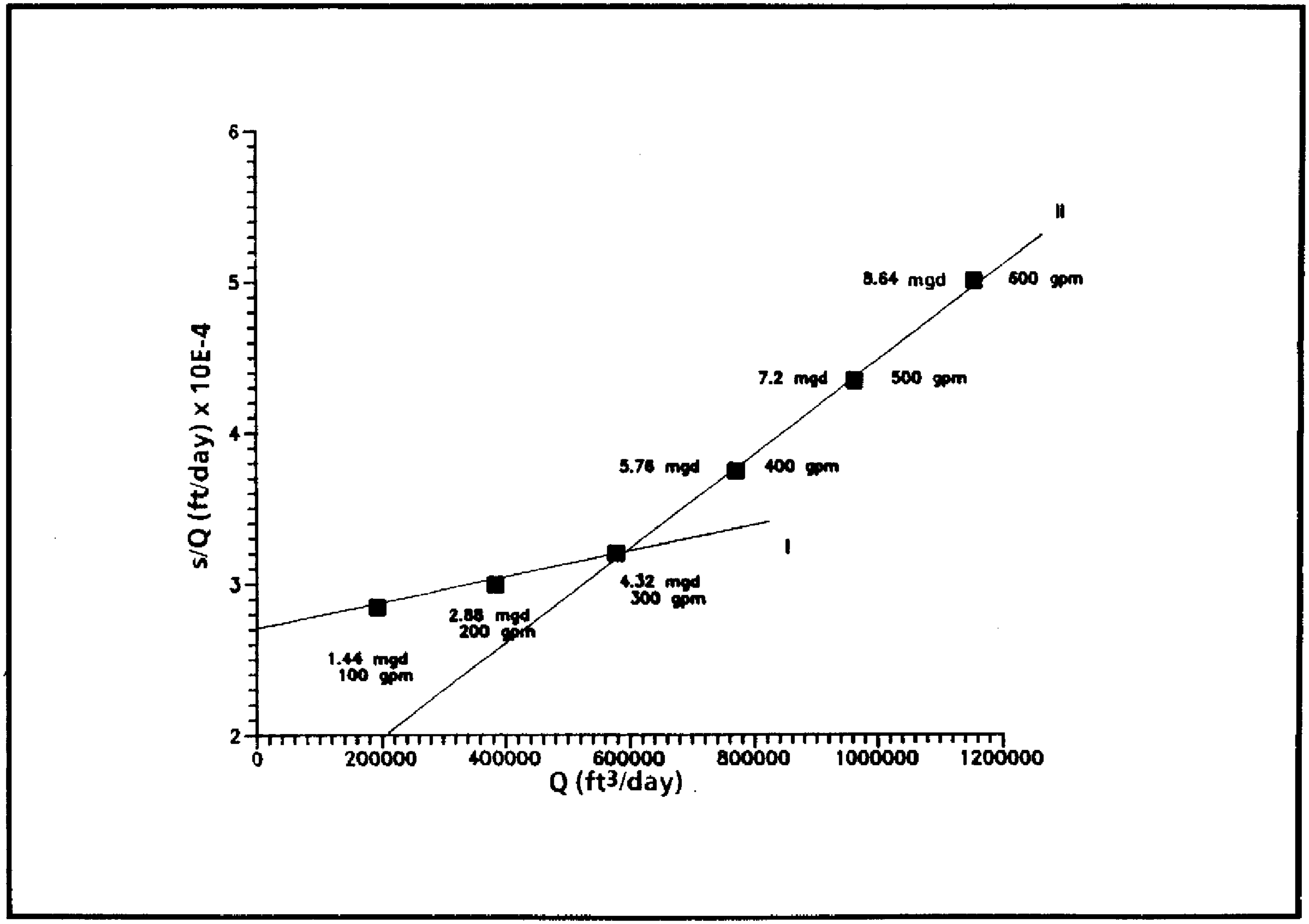

FIGURE 15. Results of Simulated Step-Drawdown Test.

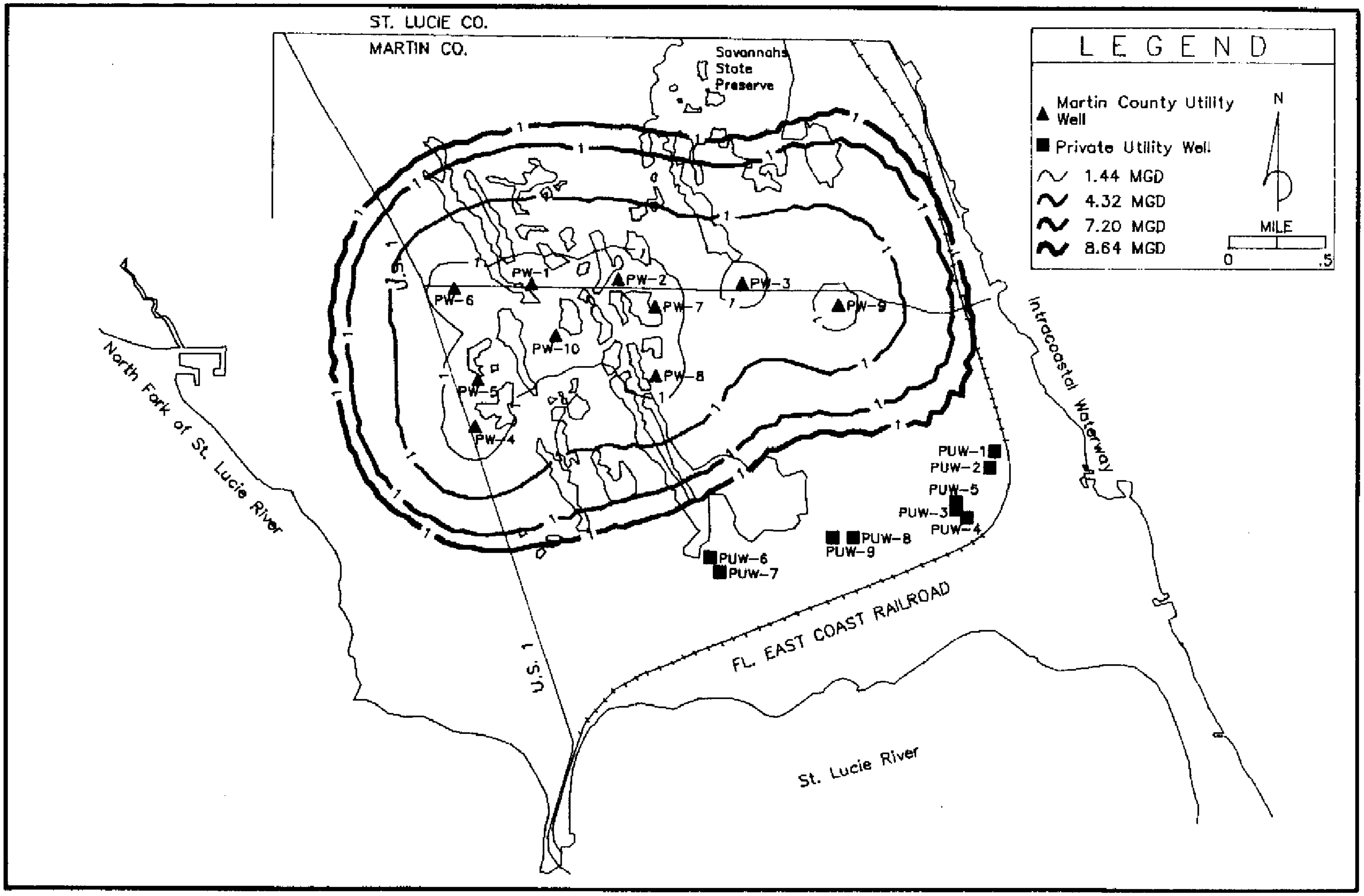

FIGURE 16. Simulated Expansion of the One Foot Cone of Depression for NMCW with Increasing Production.

The Utility hired a consultant to explore the alternatives of constructing additional wells west of the North Fork of the St. Lucie River and using Floridan water treated by desalination methodology. The existing wellfield configuration is not ideal for minimizing effects on wetlands, but due to the difficulty of siting wells away from the interior, and the limited capacity of the Surficial Aquifer System, it is not practical to attempt to optimize pumpage based on the construction of additional surficial wells on the Jensen Beach peninsula. Although difficulties arise with the use of Floridan Aquifer System water, such as increased cost, brine disposal, and current regulatory criteria which restricts the use of pumps on Floridan Aquifer System wells as a means to maintain the potentiometric surface above land surface, the Utility's plan to use Floridan Aquifer System water supplemented with Surficial Aquifer System water from the existing wellfield seems the most practical alternative at this time. This plan will provide a larger quantity of water while allowing surficial withdrawals to be optimized to minimize wetland impacts and salt water intrusion.

4. Is there a hydrologic link between the north county wellfield and the Savannas State Preserve?

The Savannas State Preserve extends about a mile into the Jensen Beach peninsula along the western edge of the Atlantic Coastal Ridge. A combination of deep and shallow fresh water marsh, the Savannas differ from the small wetlands around the wellfield in soil type and hydrologic regime. McCollum and Cruz (1981) described the soil under the Savannas as nearly level, poorly drained organic soil. Typically, there is a thin layer of fibrous peat underlain by a layer of muck from 16 to 40 inches in thickness. Below this is sand. Under average natural conditions this soil is covered by standing water for six to nine months of the year, and the water table is at a depth of less than ten inches for the rest of the year. Internal drainage is slow, and inhibited by the high water table.

The aquifer underlying the Savannas Preserve is the same one in which the NMCW wells are completed. Figure 12, representing a worst case scenario (severe drought combined with maximum permitted pumpage), showed the one foot drawdown contour for the wellfield extending out under the southernmost edge of the Savannas. Based on this expected cone of influence, it is doubtful that the north Martin County Wellfield has been a major contributor to drought conditions in the preserve. It is more likely, that the extremely dry conditions are the result of the lack of rainfall in combination with excess drainage, brought about by increased development along the edges of the preserve. However, the wellfield was shown to be impacting land (Spices Tract) that was slated to become part of the Savannas Preserve. This led to the development of the modified wellfield operating plan.

Because of its sensitivity to water table conditions, the Savannas Preserve is particularly vulnerable to drainage activities (e.g. surface water management lakes, ditches and canals), which are designed to cause local lowering of the water table.

5. What factors have contributed to the excessively dry conditions and lowered Surficial Aquifer System levels in the north Martin County peninsula?

Water levels decline when discharge from an aquifer exceeds recharge, resulting in a loss of storage. Figure 17, a water level hydrograph from inland production zone monitoring well W3-A, depicts the declining water table in the area. Over the last few years, the Jensen Beach peninsula has been suffering from decreasing rainfall (recharge) in conjunction with increasing wellfield withdrawals (discharge) (Figure 18). There are other factors, however, which affect the quantity of rainfall that eventually reaches the aquifer. Figure 19 illustrates the possible disposition of an average rainfall.

A certain portion of the gross precipitation will be intercepted by above ground objects before it reaches land surface. The amount of water intercepted is a function of the storm intensity, foliage density, and the season of the year. The portion of rainfall intercepted before reaching land surface ranges from 0% for clear bare ground, to 25% for dense forest (Restrepo, in press).

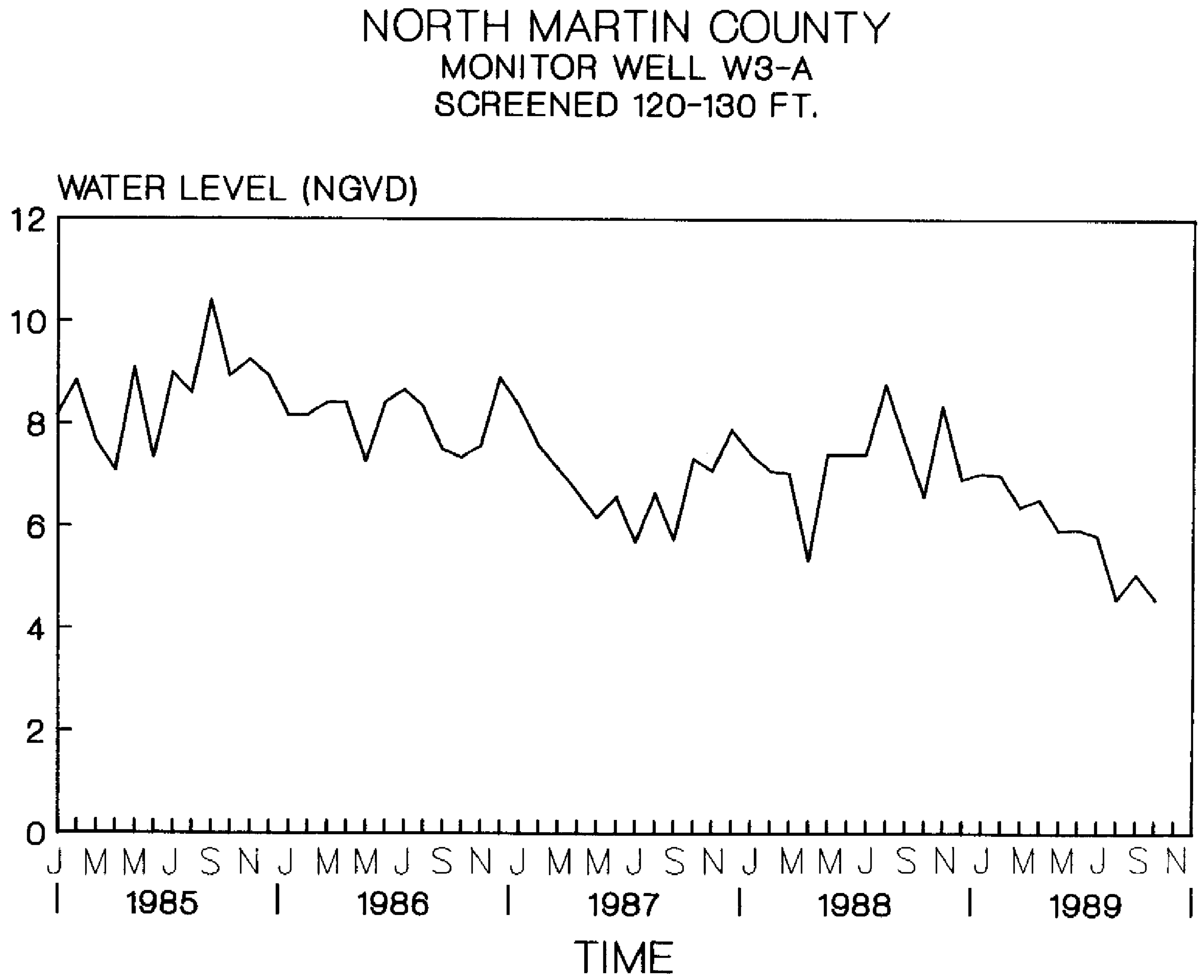

FIGURE 17. Water Level Hydrograph from Monitoring Well W3-a, Showing Water Level Decline.

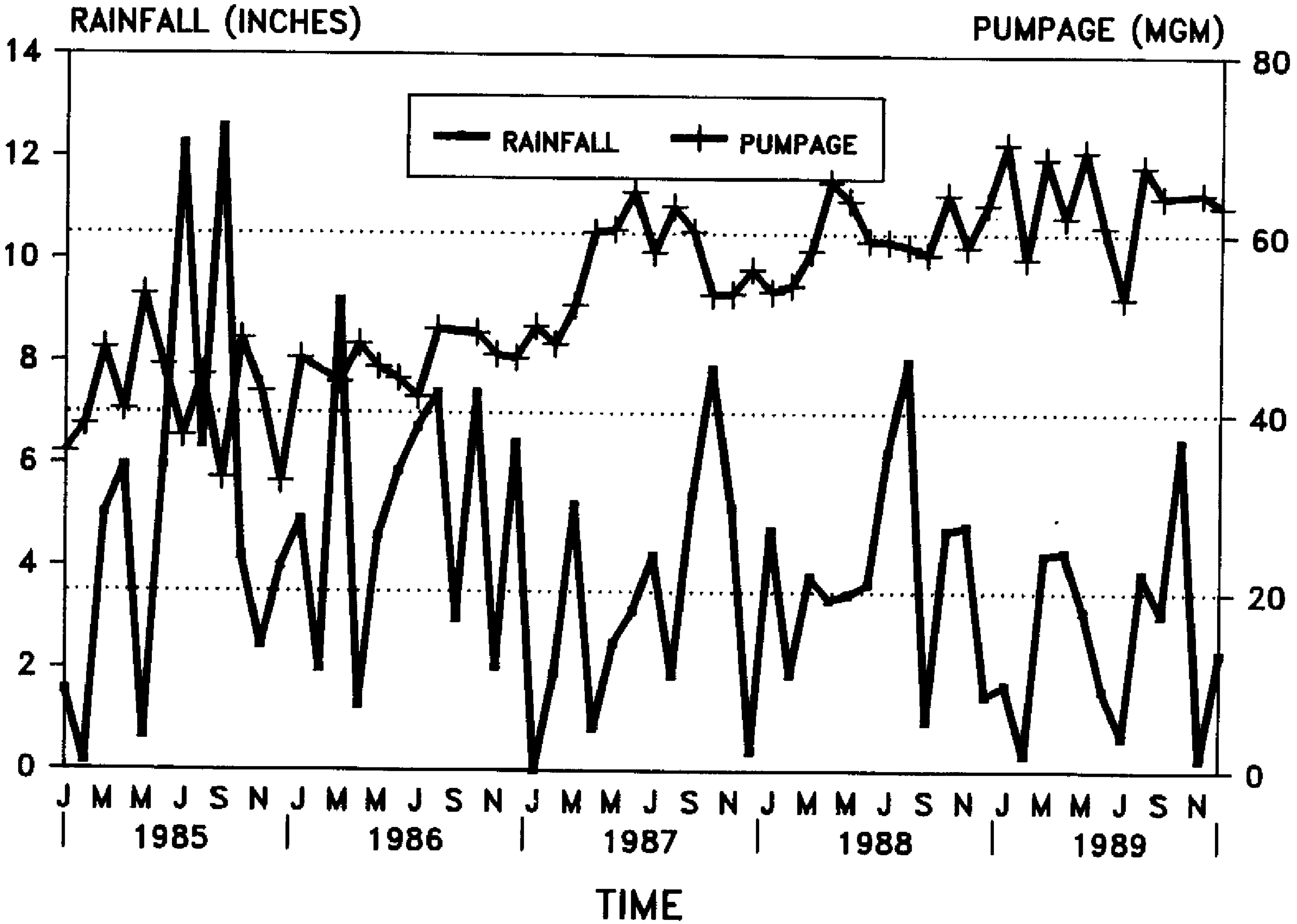

FIGURE 18. Rainfall and Pumpage Hydrograph Showing Increasing Pumpage from the Wellfield in Conjunction with Decreasing Rainfall during the Period (Jan. 85-Dec. 89)

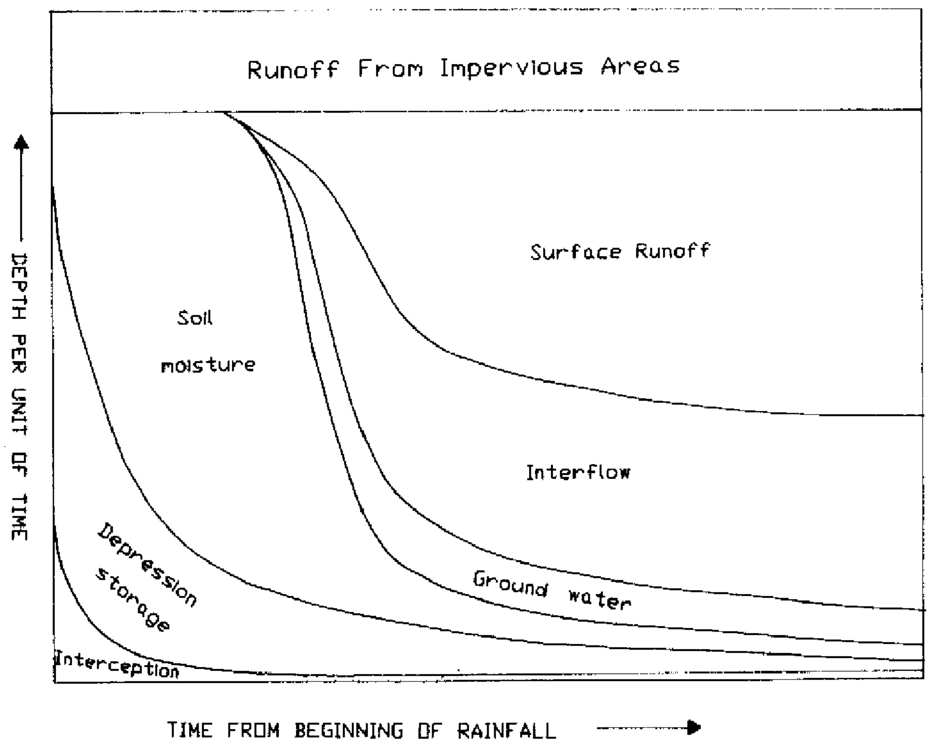

FIGURE 19. Schematic Drawing Showing the Disposition of an Average Rainfall Event (from Linsley et al., 1982)

Once reaching ground surface, precipitation may be lost (made unavailable for ground water recharge) as surface runoff, become trapped in small depressions and lost to evaporation, or infiltrate. The amount of water lost to surface runoff and depression storage is a function of the slope, storm intensity, and the percent of the area covered by impervious surfaces (parking lots, roads etc.). Construction of paved surfaces leads to decreased recharge due to increased runoff and depression storage (Figure 20a,b).

Precipitation infiltrating land surface follows one of three courses; it may 1) be retained in the unsaturated zone of the soil by capillary forces (soil moisture storage), 2) move laterally through the upper layers of the soil as interflow, or 3) percolate downward to become recharge to the aquifer.

Soil moisture may be present in the form of gravity water (in transit through the larger pore spaces), capillary water (held in the smaller pore spaces by capillary forces), and hydroscopic moisture (a thin film adhering to soil grains) (Linsley et al., 1982). During periods of prolonged drought, soil pores will dehydrate. When this occurs, less recharge reaches the aquifer because a higher percentage of the water which reaches the ground is required to re-wet the soil than under normal climactic conditions. Most of the light rains that fell on the interior of the north Martin County peninsula in 1989 were probably held as soil moisture within a few feet of land surface.

Some of the water which penetrates land surface will move as interflow to the nearest discharging area (e.g. stream channel, drainage ditch, surface water management lake). A thin soil covering with an underlying hardpan a short distance below the surface favors substantial quantities of interflow. Once it is discharged, a large portion of this water will be released back into the atmosphere through evaporation.

In addition to the deficit in rainfall, anthropogenic activities have contributed to the excessively dry conditions on the Jensen Beach peninsula through: direct discharge from the aquifer (pumpage), the construction of impervious areas which cause rainfall to be lost as surface runoff or stored in shallow depressions until it evaporates, and the construction of drainage facilities which cause local lowering of the water table. The precise extent to which these activities have contributed to drought conditions is not known.

CONCLUSIONS

1. A hardpan layer exists in the vicinity of the north Martin County Wellfield. It underlies not only wetland areas, but the pine uplands as well. Where this layer is present, it impedes the downward percolation of water, and promotes horizontal flow (interflow). It is not, however, a continuous uniform layer. The thickness of the hardpan may vary greatly over short distances, dipping, thinning and disappearing all within the same wetland. Although low permeability hardpan layers are frequently present within the soil profile, they have variable leakage characteristics and are spatially discontinuous. They do not isolate the wetlands from the underlying aquifer.

2. Because the wetlands are not hydraulically isolated from the rest of the aquifer, they are adversely impacted by wellfield withdrawals. When the water table is high, as it has historically been in this area, it causes a decrease in the infiltration rate, which impedes downward flow out of the wetlands. When the water table is depressed, as it is in the vicinity of the wellfield, a downward flow gradient is created across the hardpan layer which causes the wetland to drain more rapidly. Where the hardpan is not present, the water level in the wetland is the same as the water level in the aquifer. Model simulations have shown as much as four feet of drawdown under some isolated wetland areas as a result of pumping from the north Martin County Wellfield.

3. Simulated responses from the SFWMD's MODFLOW optimization model, MODMAN, indicated that production wells 7 and 10 have the greatest impacts on wetland areas. Wetland water levels are least sensitive to pumping from wells 6 and 9.

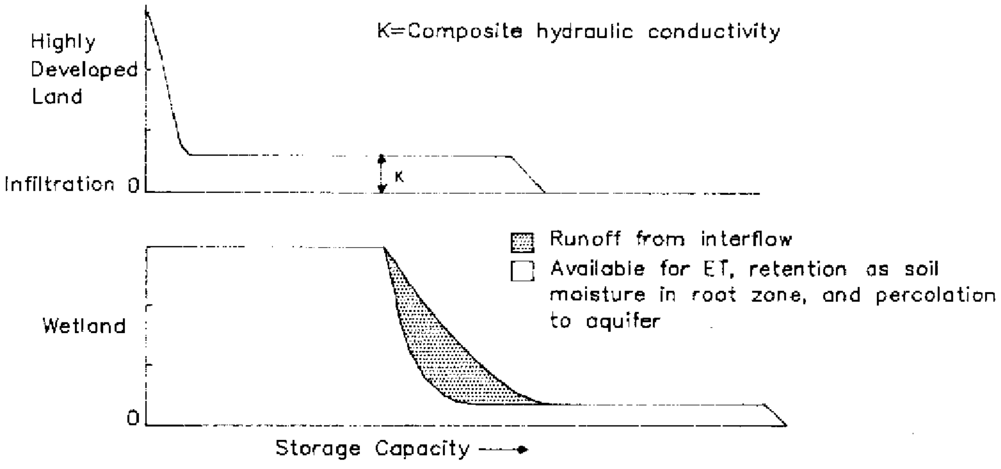

FIGURE 20(a). Schematic Showing the Difference in Storage Capacity Between Wetlands and Developed Land

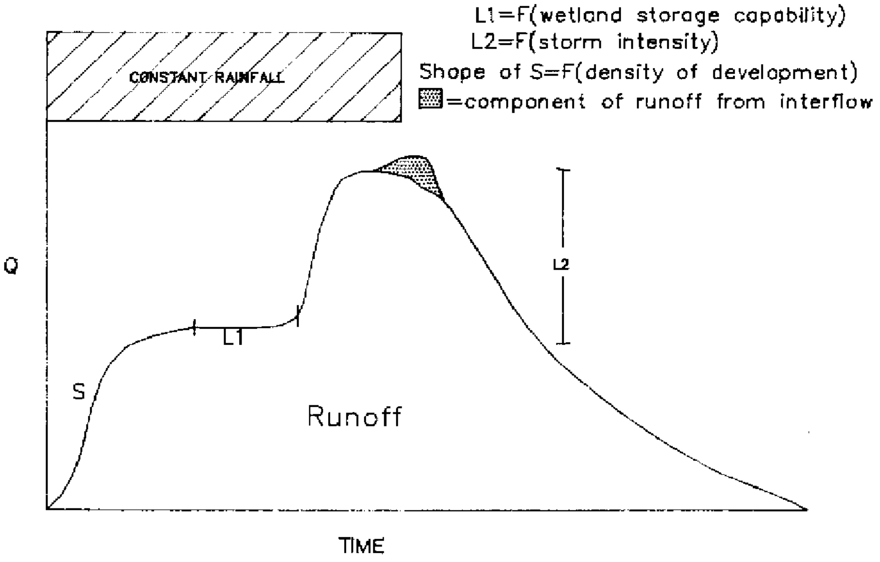

FIGURE 20(b). Shape of Runoff Hydrograph as a Function of Land Use, Storm Intensity and Wetland Storage Capability

4. Current regulatory criteria require applicants for permits including surface water management lakes to have a minimum distance of 200 feet between a surface water management lake and a wetland. The extent to which the hardpan can be perforated without draining an adjacent wetland, or intercepting its recharge, is dependent on the extent and geometry of the hardpan, and the proximity of the proposed excavation to the wetland. Because of the variability of the hardpan unit, these characteristics must be determined by further study.

   The presence of a low permeability layer, such as hardpan, at a shallow depth under land surface promotes interflow over that layer. Interflow moves over the hardpan layer from areas of higher elevation to areas of lower elevation. For this reason any excavation upslope (related to the hardpan layer) of a wetland is inadvisable as it will intercept recharge to the wetland. A safe setback distance for a downslope excavation can be determined from the hydraulic conductivity of the soil and the degree of slope of the hardpan layer. The current SFWMD regulatory criteria requiring a 200 foot setback may not be sufficient where increased interflow is induced by a restrictive hardpan layer.

5. No additional water is available for withdrawal or allocation from the Surficial Aquifer System on the Jensen Beach peninsula with the wellfields in their present configuration, without causing further impacts to the wetlands. Alternative sources of water, such as the Floridan Aquifer System, or importing Surficial Aquifer System water from inland wellfields, are necessary. A change in the SFWMD rule restricting pumps on Floridan wells in Martin and St. Lucie counties may be required in order to allow Floridan wells to be used as a source of public supply using desalination treatment.

RECOMMENDATIONS

Conflicts between wetland protection and wellfield development will become increasingly common as Martin and northern Palm Beach counties continue to develop. These areas contain wetland habitat that no longer exists throughout most of the lower east coast. Several actions must be taken now if these wetland are to protected, both in the Jensen Beach area and throughout the upper east coast:

1. Pumpage from the Surficial Aquifer System in the Jensen Beach peninsula should be optimized in order to minimize impacts on the wetlands. Permitted allocations should be modified to reflect the optimized withdrawals. In addition, permitted allocations should be further reduced as water from the desalinization plant becomes available.

2. The SFWMD should complete an evaluation of the Floridan Aquifer System as a source of public water supply. The District's criteria restricting installation of pumps on Floridan wells in Martin and St. Lucie counties should be reviewed. Other alternatives to the Surficial Aquifer System, such as conservation and reuse, should be explored and implemented where possible.

3. The District's criteria governing the construction of surface water management lakes should be studied as it relates to the site specific hydraulic and hydrogeologic characteristics. This would result in developing a criteria to allow for varying setback distances between hardpan piercing activities and wetlands on a case by case basis. This study should also include the relationship between surface water management systems, hardpan layers, and ground water levels.

REFERENCES

Collins, M.E., Ph.D., Professor of Soil Science, University of Florida Personal Communication May 1990.

Davis, J.H., 1946. The Peat Deposits of Florida. Florida Geological Survey Bulletin No. 30.

Driscoll, F.G., 1986. Groundwater and Wells. Johnson Division, St. Paul, Minnesota.

GEOTRANS, Inc., 1990. MODMAN: An Optimization Module For Modflow. GEOTRANS, Inc., Consultant Report.

Lichtler, W.F., 1960. Geologic and Groundwater Resources of Martin County, Florida. Florida Geological Survey Report of Investigations No. 23, 149p.

McCollum S.H. and O.E. Cruz, 1981. Soil Survey of Martin County Area, Florida. U.S.D.A. Soil Conservation Service.

McDonald, M.G. and A.W. Harbaugh, 1984. A Modular Three-Dimensional Finite Difference Ground-Water Flow Model. U.S. Geological Survey, National Center, Reston, Virginia.

Linsley, R.K., M.A. Kohler, and J.L. Paulhus, 1982. Hydrology for Engineers. Mcgraw-Hill Book Co., New York.

Miller, W.L., 1980. Geologic Aspects of the Surficial Aquifer in the Upper East Coast Planning Area, Southeast Florida. USGS Water Resources Investigations Open-File Report 80-586, 2 map sheets.

Mitsch, W.J. and J.G. Gosselink, 1986. Wetlands. Van Nostrand Reinhold Co., Inc., New York.

James M. Montgomery, Consulting Engineers, Inc., 1988. Evaluation of Impacts of Wellfield Withdrawals on Wetlands in the Vicinity of the North Martin County Wellfield, Phase I, Data Review and Assessment. James M. Montgomery, Consulting Engineers, Inc. Consultant Report

James M. Montgomery, Consulting Engineers, Inc., 1989. North Martin County Wellfield Wetlands Impact Study, Phase II, Aquifer Performance Test. James M. Montgomery, Consulting Engineers, Inc. Consultant Report

Nealon D., Shih G., Trost S.M., Opalat S., Fan A., Adams B., 1987. Martin County Water Resource Assessment, South Florida Water Management District Special Report, May, 1987.

O'Brien, A.L. and W.S. Motts, 1980. Hydrogeologic Evaluation of Wetland Basins for Land Use Planning, Water Resources Bulletin Vol. 16, No. 5, pp 785-789.

Restrepo, J., (unpublished,1989). Water Recharge to and Evapotranspiration from the Aquifer System. South Florida Water Management District.

Shine, M.J., Don G. J. Padgett, and William M. Barfknecht, 1989. Groundwater Resource Assessment of Eastern Palm Beach County Florida. South Florida Water Management District Techincal Publication 89-4.

Strack, O.D., 1989. Groundwater Mechanics. Prentice Hall, Englewood Cliffs, New Jersey.

Todd, K.D., 1980. Groundwater Hydrology. John Wiley & Sons, New York.

APPENDIX I

MODEL CALIBRATION HYDROGRAPHS

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       STATION:   S3-B                       STATION:   W1-B

       LAYER:    1                           LAYER:    1
       ROW:   54                             ROW:   24
       COLUMN:    23                         COLUMN:    33

      -3         7        17                -3         7        17
       +.........+.........+                 +.........+.........+

FEB 87 :     +*                       FEB 87 M             *
MAR 87 :    + *                       MAR 87 M             *
APR 87 :    +*                        APR 87 M            *
MAY 87 :  +  *                        MAY 87 M            *
JUN 87 :   + *                        JUN 87 M            *
JUL 87 :   + *                        JUL 87 M            *
AUG 87 :   +*                         AUG 87 M           *
SEP 87 :   + *                        SEP 87 M            *
OCT 87 :  +   *                       OCT 87 M             *
NOV 87 :    + *                       NOV 87 M             *
DEC 87 :   + *                        DEC 87 M            *
JAN 88 :     +*                       JAN 88 M             *
FEB 88 :   + *                        FEB 88 M            *
MAR 88 :   + *                        MAR 88 M            *
APR 88 :    +*                        APR 88 M            *
MAY 88 :    +*                        MAY 88 M            *
JUN 88 M     *                        JUN 88 M            *
JUL 88 :   + *                        JUL 88 M            *
AUG 88 :    *                         AUG 88 M            *
SEP 88 :    +*                        SEP 88 M            *
OCT 88 :   + *                        OCT 88 M            *
NOV 88 :   + *                        NOV 88 M            *
DEC 88 M  *                           DEC 88 M          *
JAN 89 :   *+                         JAN 89 M          *
FEB 89 :   *+                         FEB 89 M          *
MAR 89 :    *                         MAR 89 M          *
APR 89 :   +*                         APR 89 M          *
MAY 89 :   +*                         MAY 89 :          *
JUN 89 :   *                          JUN 89 :          *
JUL 89 :   *                          JUL 89 :         *
AUG 89 :   *                          AUG 89 :         +*
SEP 89 :    *                         SEP 89 :        + *
OCT 89 :   *                          OCT 89 :        + *
NOV 89 :  +*                          NOV 89 :        +*
DEC 89 :  +*                          DEC 89 M        *

* = simulated water levels
+ = observed water levels
M = missing data
           (if observed agrees with simulated, only a * is printed)
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```
       STATION:   W3-B                        STATION:   W4-B

       LAYER:    1                            LAYER:    1
       ROW:   51                              ROW:   34
       COLUMN:    59                          COLUMN:    46

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       +.........+.........+                  +.........+.........+

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MAR 87 M          *                    MAR 87 M              *
APR 87 :        + *                    APR 87 :       +     *
MAY 87 :       + *                     MAY 87 :            *
JUN 87 :         *                     JUN 87 :           +*
JUL 87 :       + *                     JUL 87 :         +  *
AUG 87 :       + *                     AUG 87 :          +*
SEP 87 :       + *                     SEP 87 :         +  *
OCT 87 :         +*                    OCT 87 :            +*
NOV 87 :        + *                    NOV 87 :             *+
DEC 87 :         +*                    DEC 87 :           +*
JAN 88 :        + *                    JAN 88 M             *
FEB 88 :        +*                     FEB 88 M            *
MAR 88 :        +*                     MAR 88 :         +  *
APR 88 :       + *                     APR 88 :       +    *
MAY 88 :        +*                     MAY 88 :       +    *
JUN 88 :        +*                     JUN 88 :      +     *
JUL 88 :        + *                    JUL 88 :       +    *
AUG 88 :          *                    AUG 88 :       +    *
SEP 88 M         *                     SEP 88 :      +     *
OCT 88 :         *                     OCT 88 :       +    *
NOV 88 :        +*                     NOV 88 :       +    *
DEC 88 :         *                     DEC 88 :        + *
JAN 89 :        *                      JAN 89 M         *
FEB 89 :        *                      FEB 89 :        *
MAR 89 :        *                      MAR 89 M        *
APR 89 :        *                      APR 89 :       *
MAY 89 :        *                      MAY 89 :      * +
JUN 89 :        *                      JUN 89 :      * +
JUL 89 :       *                       JUL 89 :     * +
AUG 89 :       +*                      AUG 89 :      *+
SEP 89 :      + *                      SEP 89 :   + *
OCT 89 :     + *                       OCT 89 :   +*
NOV 89 :      +*                       NOV 89 :   +*
DEC 89 :      +*                       DEC 89 M
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* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
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         COLUMN:    72                          COLUMN:    30

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         +.........+.........+                  +.........+.........+

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  MAR 87 M                 *             MAR 87 M      *
  APR 87 :              + *              APR 87 :    + *
  MAY 87 :              + *              MAY 87 :     +*
  JUN 87 :             + *               JUN 87 :    +*
  JUL 87 :             + *               JUL 87 :     +*
  AUG 87 :             + *               AUG 87 :    +*
  SEP 87 :             + *               SEP 87 :    + *
  OCT 87 :               +*              OCT 87 :      *
  NOV 87 :                *              NOV 87 :      +*
  DEC 87 :               *               DEC 87 :     +*
  JAN 88 :              + *              JAN 88 :     +*
  FEB 88 :               *               FEB 88 M      *
  MAR 88 :               *               MAR 88 :    + *
  APR 88 :               *               APR 88 :    + *
  MAY 88 :              +*               MAY 88 :    + *
  JUN 88 :              +*               JUN 88 :  +  *
  JUL 88 :              +*               JUL 88 :     +*
  AUG 88 :              +*               AUG 88 :   + *
  SEP 88 :             + *               SEP 88 :   +*
  OCT 88 :              +*               OCT 88 :    +*
  NOV 88 :              +*               NOV 88 :    + *
  DEC 88 :             *+                DEC 88 :   *+
  JAN 89 :             *+                JAN 89 :    *
  FEB 89 :            *+                 FEB 89 :    *
  MAR 89 :             *                 MAR 89 :    +*
  APR 89 :            *+                 APR 89 :    *
  MAY 89 :            *                  MAY 89 :   + *
  JUN 89 :            *                  JUN 89 :   +*
  JUL 89 :           *                   JUL 89 :   +*
  AUG 89 :           +*                  AUG 89 :    +*
  SEP 89 :           +*                  SEP 89 :    +*
  OCT 89 M           *                   OCT 89 :    *
  NOV 89 :          +*                   NOV 89 :    *
  DEC 89 :          +*                   DEC 89 :   + *

* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
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         COLUMN:    44                          COLUMN:    28

         -3         7        17                 -3         7        17
         +.........+.........+                  +.........+.........+

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  MAR 87 M           *                   MAR 87 M          *
  APR 87 :          *                    APR 87 :        +*
  MAY 87 :         +*                    MAY 87 :       + *
  JUN 87 :       +  *                    JUN 87 :      + *
  JUL 87 :          *                    JUL 87 :      + *
  AUG 87 :         +*                    AUG 87 :      + *
  SEP 87 :         +*                    SEP 87 :     +  *
  OCT 87 :          +*                   OCT 87 :         *
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  DEC 87 :        + *                    DEC 87 :      +  *
  JAN 88 :         + *                   JAN 88 :        +*
  FEB 88 M           *                   FEB 88 M         *
  MAR 88 :         + *                   MAR 88 :        *
  APR 88 :         +*                    APR 88 M        *
  MAY 88 :        + *                    MAY 88 :       +*
  JUN 88 :        + *                    JUN 88 :       +*
  JUL 88 :         +*                    JUL 88 :        +*
  AUG 88 :         + *                   AUG 88 :         *
  SEP 88 :         +*                    SEP 88 :       +*
  OCT 88 :          *                    OCT 88 :       +*
  NOV 88 :         +*                    NOV 88 :      + *
  DEC 88 :        *+                     DEC 88 :     + *
  JAN 89 :        *+                     JAN 89 :       *
  FEB 89 :        *                      FEB 89 :     *+
  MAR 89 :       + *                     MAR 89 :      *
  APR 89 :        +*                     APR 89 :     *
  MAY 89 :        +*                     MAY 89 :     *+
  JUN 89 :        *                      JUN 89 :     *+
  JUL 89 :        *+                     JUL 89 :    *+
  AUG 89 M        *                      AUG 89 :    *+
  SEP 89 M         *                     SEP 89 :    *+
  OCT 89 :      + *                      OCT 89 :    *+
  NOV 89 :       *                       NOV 89 :  +*
  DEC 89 M       *                       DEC 89 :  +*

* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
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```
       STATION:   MCA-S                        STATION:   MCB-S

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        +.........+.........+                   +.........+.........+

FEB 87 M                *              FEB 87 M                *
MAR 87 M                *              MAR 87 M                *
APR 87 M               *               APR 87 M               *
MAY 87 M               *               MAY 87 M              *
JUN 87 M               *               JUN 87 M              *
JUL 87 M               *               JUL 87 M              *
AUG 87 M              *                AUG 87 M             *
SEP 87 M               *               SEP 87 M              *
OCT 87 M                *              OCT 87 M              *
NOV 87 M                *              NOV 87 M               *
DEC 87 M               *               DEC 87 M              *
JAN 88 M                *              JAN 88 M              *
FEB 88 M               *               FEB 88 M             *
MAR 88 M               *               MAR 88 M             *
APR 88 M               *               APR 88 M             *
MAY 88 M               *               MAY 88 M            *
JUN 88 M               *               JUN 88 M            *
JUL 88 M               *               JUL 88 M            *
AUG 88 M               *               AUG 88 :            +*
SEP 88 :               *               SEP 88 :           +*
OCT 88 :               *               OCT 88 :           +*
NOV 88 :               *               NOV 88 :          + *
DEC 88 :            * +                DEC 88 :         +*
JAN 89 :             *+                JAN 89 :         +*
FEB 89 :             *+                FEB 89 :        * +
MAR 89 :             *+                MAR 89 :          *+
APR 89 :             *+                APR 89 :         *
MAY 89 :             *+                MAY 89 :        +*
JUN 89 :             *+                JUN 89 :         *
JUL 89 :             *                 JUL 89 :        *+
AUG 89 :             *                 AUG 89 :        +*
SEP 89 :             *                 SEP 89 :        *+
OCT 89 :             *                 OCT 89 :        *+
NOV 89 :             *                 NOV 89 :       * +
DEC 89 :             *                 DEC 89 :       *+

* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
```

```
         STATION:  MCC-S                       STATION:  S1-B

         LAYER:    1                           LAYER:   2
         ROW:   47                             ROW:  24
         COLUMN:    43                         COLUMN:   13

        -3         7        17                -4         6        16
         +.........+.........+                 +.........+.........+

  FEB 87 M               *              FEB 87 :     +*
  MAR 87 M               *              MAR 87 M      *
  APR 87 M             *                APR 87 :    +*
  MAY 87 M             *                MAY 87 :    +*
  JUN 87 M             *                JUN 87 :    +*
  JUL 87 M             *                JUL 87 :    +*
  AUG 87 M            *                 AUG 87 :    +*
  SEP 87 M             *                SEP 87 :   + *
  OCT 87 M             *                OCT 87 :    + *
  NOV 87 M              *               NOV 87 :      *
  DEC 87 M             *                DEC 87 :     +*
  JAN 88 M              *               JAN 88 :    + *
  FEB 88 M             *                FEB 88 :    + *
  MAR 88 M             *                MAR 88 :     *
  APR 88 M            *                 APR 88 :     *
  MAY 88 M            *                 MAY 88 :    +*
  JUN 88 M            *                 JUN 88 :    +*
  JUL 88 M            *                 JUL 88 :    +*
  AUG 88 M             *                AUG 88 :    +*
  SEP 88 :          + *                 SEP 88 :    +*
  OCT 88 :         +  *                 OCT 88 :   + *
  NOV 88 :         +  *                 NOV 88 :    +*
  DEC 88 :         +*                   DEC 88 :  * +
  JAN 89 :        + *                   JAN 89 :   *+
  FEB 89 :        +*                    FEB 89 :   *
  MAR 89 :        + *                   MAR 89 :   +*
  APR 89 M          *                   APR 89 :    *
  MAY 89 :        + *                   MAY 89 :   +*
  JUN 89 :       + *                    JUN 89 :   +*
  JUL 89 :        +*                    JUL 89 :   +*
  AUG 89 :       + *                    AUG 89 :   +*
  SEP 89 :       + *                    SEP 89 :    *
  OCT 89 :       + *                    OCT 89 :    *
  NOV 89 :       +*                     NOV 89 :    *
  DEC 89 :      +*                      DEC 89 :   +*

* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
```

```
       STATION:   S2-A

       LAYER:    2
       ROW:   55
       COLUMN:    12

      -5         5         15
       +.........+.........+

FEB 87 M     *
MAR 87 M     *
APR 87 M    *
MAY 87 M    *
JUN 87 M    *
JUL 87 M    *
AUG 87 M    *
SEP 87 M    *
OCT 87 M     *
NOV 87 M     *
DEC 87 M     *
JAN 88 M     *
FEB 88 M     *
MAR 88 M     *
APR 88 M    *
MAY 88 M    *
JUN 88 M    *
JUL 88 M    *
AUG 88 M     *
SEP 88 M    *
OCT 88 M    *
NOV 88 M    *
DEC 88 M   *
JAN 89 :    *
FEB 89 :   +*
MAR 89 :   +*
APR 89 :  + *
MAY 89 :    *
JUN 89 :    *
JUL 89 :    *
AUG 89 :    *
SEP 89 :    *
OCT 89 :    *
NOV 89 :    *
DEC 89 :    *
```

```
       STATION:   S3-A

       LAYER:    2
       ROW:   54
       COLUMN:    23

      -3         7         17
       +.........+.........+

FEB 87 :     +*
MAR 87 M      *
APR 87 :     *
MAY 87 :     *
JUN 87 :    +*
JUL 87 :    +*
AUG 87 :    +*
SEP 87 :    +*
OCT 87 :   +  *
NOV 87 :    + *
DEC 87 :  +  *
JAN 88 :    + *
FEB 88 :   + *
MAR 88 :    +*
APR 88 :    +*
MAY 88 :    +*
JUN 88 :     *
JUL 88 :   + *
AUG 88 :   + *
SEP 88 :     *+
OCT 88 :    +*
NOV 88 :    +*
DEC 88 :  *+
JAN 89 :   *+
FEB 89 :   *+
MAR 89 :   +*
APR 89 :   +*
MAY 89 :   +*
JUN 89 :   *
JUL 89 :   *
AUG 89 :   *+
SEP 89 :    *
OCT 89 :   *+
NOV 89 :   *+
DEC 89 :  +*
```

```
* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
```

```
      STATION:   W1-A

      LAYER:    2
      ROW:     24
      COLUMN:  33

      -3         7         17
       +.........+.........+

FEB 87 M             *
MAR 87 M             *
APR 87 M            *
MAY 87 M            *
JUN 87 M            *
JUL 87 M            *
AUG 87 M           *
SEP 87 M            *
OCT 87 M             *
NOV 87 M             *
DEC 87 M            *
JAN 88 M             *
FEB 88 M            *
MAR 88 M            *
APR 88 M            *
MAY 88 M            *
JUN 88 M            *
JUL 88 M            *
AUG 88 M            *
SEP 88 M            *
OCT 88 M            *
NOV 88 M            *
DEC 88 M          *
JAN 89 M          *
FEB 89 M         *
MAR 89 M          *
APR 89 M          *
MAY 89 :          *
JUN 89 :          *
JUL 89 :         *
AUG 89 :         +*
SEP 89 :        + *
OCT 89 :        +*
NOV 89 :         *
DEC 89 :        *
```

```
       STATION:   W7-A

       LAYER:    2
       ROW:   44
       COLUMN:    28

     - 3         7         17
       +.........+.........+

FEB 87 :    +     *
MAR 87 M          *
APR 87 :      +  *
MAY 87 :     +  *
JUN 87 :    +  *
JUL 87 :     +  *
AUG 87 M        *
SEP 87 :     +  *
OCT 87 :       + *
NOV 87 :        +*
DEC 87 :         *+
JAN 88 :       + *
FEB 88 M        *
MAR 88 :     +  *
APR 88 :   +    *
MAY 88 :     +  *
JUN 88 :   +    *
JUL 88 :     +  *
AUG 88 :        +*
SEP 88 :   +    *
OCT 88 :       +*
NOV 88 :       +*
DEC 88 :       *
JAN 89 :    + *
FEB 89 :   + *
MAR 89 :   + *
APR 89 :   + *
MAY 89 :   + *
JUN 89 :   +*
JUL 89 :   +*
AUG 89 :   +*
SEP 89 :   +*
OCT 89 :   +*
NOV 89 :   *
DEC 89 :  +*
```

```
* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
```

```
         STATION:   W2-D                       STATION:   W3-A

         LAYER:    2                           LAYER:    2
         ROW:     65                           ROW:   51
         COLUMN:  44                           COLUMN:    59

        -3         7        17                -3         7        17
         +.........+.........+                 +.........+.........+

  FEB 87 :           *                  FEB 87 :         +   *
  MAR 87 M           *                  MAR 87 M             *
  APR 87 :          *                   APR 87 :        +   *
  MAY 87 :         +*                   MAY 87 :        +  *
  JUN 87 :         +*                   JUN 87 :        +  *
  JUL 87 :          *                   JUL 87 :       +   *
  AUG 87 :         +*                   AUG 87 :       +   *
  SEP 87 :         +*                   SEP 87 :       +   *
  OCT 87 :          +*                  OCT 87 :         +  *
  NOV 87 :         + *                  NOV 87 :         +  *
  DEC 87 :         + *                  DEC 87 :         + *
  JAN 88 :         + *                  JAN 88 :         +  *
  FEB 88 M           *                  FEB 88 :         + *
  MAR 88 :         +*                   MAR 88 :         + *
  APR 88 :         +*                   APR 88 :       +   *
  MAY 88 :         +*                   MAY 88 :         + *
  JUN 88 :        + *                   JUN 88 :         + *
  JUL 88 :         +*                   JUL 88 :         + *
  AUG 88 :         + *                  AUG 88 :          + *
  SEP 88 :        + *                   SEP 88 M           *
  OCT 88 :         +*                   OCT 88 :        + *
  NOV 88 :         +*                   NOV 88 :         +*
  DEC 88 :        *+                    DEC 88 :        + *
  JAN 89 :        *+                    JAN 89 :         +*
  FEB 89 :        *                     FEB 89 :         *
  MAR 89 :        +*                    MAR 89 :        +*
  APR 89 :        *                     APR 89 :        +*
  MAY 89 :        *                     MAY 89 :       + *
  JUN 89 :        *                     JUN 89 :       + *
  JUL 89 :        *+                    JUL 89 :       +*
  AUG 89 :       +*                     AUG 89 :      + *
  SEP 89 :      + *                     SEP 89 :       +*
  OCT 89 :     +  *                     OCT 89 :      + *
  NOV 89 :     +  *                     NOV 89 :      + *
  DEC 89 :     + *                      DEC 89 :      +*

* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
```

```
       STATION:   W4-A

       LAYER:     2
       ROW:    34
       COLUMN:    46

      -3         7         17
       +.........+.........+

FEB 87 :            + *
MAR 87 M             *
APR 87 :            *
MAY 87 :       +   *
JUN 87 :          +*
JUL 87 :          +*
AUG 87 :          +*
SEP 87 :          +*
OCT 87 :       +    *
NOV 87 :            *
DEC 87 :            *
JAN 88 M            *
FEB 88 M            *
MAR 88 :           * +
APR 88 :          +*
MAY 88 :          +*
JUN 88 :          +*
JUL 88 :          +*
AUG 88 M            *
SEP 88 :          +*
OCT 88 :         + *
NOV 88 :         + *
DEC 88 :         *+
JAN 89 M        *
FEB 89 :       *
MAR 89 M      *
APR 89 :     *+
MAY 89 :     *  +
JUN 89 :    *   +
JUL 89 :    *+
AUG 89 :     *
SEP 89 :    *+
OCT 89 :  + *
NOV 89 :  +*
DEC 89 :  +*
```

```
       STATION:   W6-A

       LAYER:     2
       ROW:    39
       COLUMN:    72

      -3         7         17
       +.........+.........+

FEB 87 :                +*
MAR 87 M                 *
APR 87 :               +*
MAY 87 :               *
JUN 87 :              +*
JUL 87 :              +*
AUG 87 :             +*
SEP 87 :              +*
OCT 87 :                *
NOV 87 :               +*
DEC 87 :               *
JAN 88 :               *
FEB 88 :               *
MAR 88 :               *
APR 88 :              +*
MAY 88 :              *
JUN 88 :              *
JUL 88 :              +*
AUG 88 :              +*
SEP 88 :             +*
OCT 88 :             + *
NOV 88 :             + *
DEC 88 :             *
JAN 89 :             *
FEB 89 :            *+
MAR 89 :            +*
APR 89 :            *+
MAY 89 :           +*
JUN 89 :           +*
JUL 89 :           *
AUG 89 :           *
SEP 89 :          +*
OCT 89 :          +*
NOV 89 :          *
DEC 89 :          *
```

```
* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
```

```
       STATION:   S4-A

       LAYER:    2
       ROW:   73
       COLUMN:    30

      -3         7        17
       +.........+.........+

FEB 87 :    +*
MAR 87 M     *
APR 87 :   + *
MAY 87 :   +*
JUN 87 :   +*
JUL 87 :   +*
AUG 87 :   +*
SEP 87 :   + *
OCT 87 :    +*
NOV 87 :     *
DEC 87 :    +*
JAN 88 :   + *
FEB 88 M     *
MAR 88 :    +*
APR 88 :   + *
MAY 88 :    +*
JUN 88 :  + *
JUL 88 :    +*
AUG 88 M     *
SEP 88 :   +*
OCT 88 :   + *
NOV 88 :   + *
DEC 88 :  *+
JAN 89 :   *
FEB 89 :   *
MAR 89 :   +*
APR 89 :   *
MAY 89 :  + *
JUN 89 :  +*
JUL 89 :   *
AUG 89 :   +*
SEP 89 :   +*
OCT 89 :   +*
NOV 89 :  +*
DEC 89 :  +*
```

```
       STATION:   MCA-D

       LAYER:    2
       ROW:   12
       COLUMN:    52

      -3         7        17
       +.........+.........+

FEB 87 M               *
MAR 87 M                *
APR 87 M               *
MAY 87 M               *
JUN 87 M              *
JUL 87 M               *
AUG 87 M              *
SEP 87 M               *
OCT 87 M               *
NOV 87 M                *
DEC 87 M               *
JAN 88 M                *
FEB 88 M               *
MAR 88 M               *
APR 88 M               *
MAY 88 M               *
JUN 88 M              *
JUL 88 M               *
AUG 88 M               *
SEP 88 :              +*
OCT 88 :              +*
NOV 88 :               *
DEC 88 :            * +
JAN 89 :             *
FEB 89 :            *+
MAR 89 :             *+
APR 89 :             *+
MAY 89 :             *
JUN 89 :             *
JUL 89 :            +*
AUG 89 :             *
SEP 89 :             *
OCT 89 :            +*
NOV 89 :            +*
DEC 89 :            *
```

```
* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
```

```
       STATION:   MCC-D

       LAYER:    2
       ROW:   47
       COLUMN:    43

      -3         7        17
       +.........+.........+

FEB 87 M               *
MAR 87 M               *
APR 87 M             *
MAY 87 M             *
JUN 87 M             *
JUL 87 M             *
AUG 87 M            *
SEP 87 M             *
OCT 87 M             *
NOV 87 M              *
DEC 87 M             *
JAN 88 M             *
FEB 88 M             *
MAR 88 M             *
APR 88 M            *
MAY 88 M            *
JUN 88 M            *
JUL 88 M            *
AUG 88 M             *
SEP 88 :         +  *
OCT 88 :        +   *
NOV 88 :        +   *
DEC 88 :        + *
JAN 89 :       +  *
FEB 89 :        +*
MAR 89 :        + *
APR 89 M         *
MAY 89 :       + *
JUN 89 :       + *
JUL 89 :      +  *
AUG 89 :      +  *
SEP 89 :      +  *
OCT 89 :      +  *
NOV 89 :      + *
DEC 89 :      + *
```

```
* = simulated water levels
+ = observed water levels
M = missing data
            (if observed agrees with simulated, only a * is printed)
```