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A GROUND WATER
DROUGHT MANAGEMENT MODEL
FOR
COLLIER COUNTY, FLORIDA

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A GROUND WATER DROUGHT MANAGEMENT MODEL FOR COLLIER COUNTY, FLORIDA

by

George Shih
Wm. Scott Burns
Richard F. Bower

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Hydrogeology Division
Department of Research and Evaluation
South Florida Water Management District
West Palm Beach, Florida

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EXECUTIVE SUMMARY

Ground water drought can be defined as a depletion of aquifer storage resulting from a lack of recharge and associated increases in demand which threatens the resource or results in interruption of supply. Interruption of supply could be caused by excessive drawdowns in the aquifer, a deterioration in water quality or both. In south Florida, deficits in storage occur naturally during the normal dry season. However, the increased demands associated with growth compounds the effects of normal dry season impacts. This has resulted in an increased frequency of resource threatening conditions along the lower west coast.

To minimize potential losses from a ground water drought, the District has been empowered to establish and implement a water shortage management plan (373.246(1) Florida Statutes). One of the goals of this plan is "to provide advance knowledge of the means by which water apportionments and reductions will be made during times of shortage" (SFWMD Rules; Chapter 40E-21). This information is derived through the comparison of current data to historical trends in order to "determine whether estimated present and anticipated available water supply within any source class will be insufficient to meet the estimated present and anticipated demands of the users form the source class". When a present or anticipated insufficiency is identified, the Governing Board may declare a water shortage.

The purpose of this study was to develop a methodology capable of providing the type of information called for in the District's Water Shortage Plan and to support water management decisions regarding ground water use. Time series ground water level and rainfall data derived from a regional monitor network were used to develop this methodology. The monitor network consists of 125 wells distributed among four fresh water aquifers in Collier County and adjacent areas. End of month water level data was used in this evaluation. The period of record was varied for each station and ranged from 3 to 25 years. Monthly rainfall data was collected from 13 stations distributed across Lee, Collier and Hendry counties.

This information is statistically analyzed to produce three levels of information: basic statistics for each individual station, water level recurrence analysis which compares existing water level against specified drought return frequencies, and a water level forecast model. The basic statistics summary includes monthly tabulations of the following parameters for each monitor well: maximum, minimum and mean water levels, plus standard deviation and skewness coefficients. The drought return frequency option compares current conditions against 1-in-5 year, 1-in-10, 1-in-25, and 1-in-50 year water levels on a monthly basis. The forecast models utilize multi-variate time series methods and transfer correlation models to identify historic trends and relationships between rainfall and ground water data. Forecasts are based on extensions of these trends up to six months in the future. The forecasted values for each station are established on the basis of minimizing estimation error. As a result, the model is self calibrating. Stations with over six years of records are used for generating drought frequency evaluations. Water level forecasts and statistical summaries are performed on all stations in the network.

There are two inherent limitations associated with the methodologies applied in this study. The first is that the model contains no explicit expression of the constraints on ground water availability. This is because such constraints have not been concisely defined throughout the District. As a result, the levels of drought can be based only on comparison to past records. In rapidly growing areas,

record lows are being established more frequently as demands on the resources increase. Record low levels themselves do not necessarily translate to damage to the resource.

The second limitation on the methodology is that the model does not respond rapidly to the addition or deletion of stress on the system nor can the model be used to predict the impacts of new development. This is due to the fact that the modeling is based on past data. For these reasons, the results of this analytic method should be combined with sound professional judgment in the formulation of water shortage declarations and implementation of water use restrictions.

It is recommended that this methodology be expanded into other counties which have suitable monitor networks in place. In addition, two additions to this methodology are proposed to improve water management decisions. These include:

1) The incorporation of water use data in a Geographic Information System (GIS) format to identify the users and the levels of demands specific to the areas under stress.

2) The integration of regional ground water flow models which will allow for the evaluation of impacts of proposed water restrictions on future water levels.

Due to the dependence of the monitor well data on the accuracy of the water level forecasting, it is important to maintain monthly data collection for all existing wells and to replace destroyed wells. Finally, it is recommended that work continue to define the constraints on aquifer yield. Work effort in this area includes the development of regional flow models, determination of the dynamics of saltwater movement and the development of comprehensive water use plans.

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ACKNOWLEDGEMENTS

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ABSTRACT

An interactive ground water monitoring and management program has been developed which uses historic trends in ground water level and rainfall data to assess and project conditions in four aquifers in southwest Florida. The assessment of conditions consists of three elements: a) summary of basic statistics consisting of monthly mean, maximum and minimum levels, standard deviation, and skewness coefficient, b) water level return frequency analysis based on a Pearson Type III distribution, and c) water level forecast models. Projections of water levels, up to six months into the future, were developed using Box and Jenkins multi-variate time series modeling techniques. Independent uni-variate models for each of the 125 monitor wells and 13 rainfall stations (plus one mean rainfall series) were developed. Next, transfer function models relating rainfall to ground water levels were developed by pairing each ground water monitor station to a rainfall series. Approximately 200 potential model combinations were identified. After eliminating duplicate models, a total of 58 time series model types were identified for the ground water stations. Each of these 58 models were tested and final forecast models were identified based on reduction of the forecast error.

Input and output to the model is maintained through user-friendly interactive programs. Output options include report summary of basic statistics, hydrographs, water level contour maps, water level forecast hydrographs, water level recurrence hydrographs, and drought frequency contour maps. Future updates to this system will incorporate water use information, canal stage interactions, and a complete ground water flow model.

INTRODUCTION

In accordance with legislative mandate, the South Florida Water Management District adopted a water shortage plan in 1982 as the primary tool to manage water allocations in times of drought (373.246(1) Florida Statutes, and Chapter 40E-21, Florida Administrative Code). The District's Water Shortage Plan provides for the collection of surface and ground water data to determine the status of the resources as well as provisions for allocating water in times of drought. With respect to monitoring, the plan requires that the District routinely monitor the condition of the water resources to determine water availability and user demands for the present and future for each source.

Data collection and evaluation methodologies are generally source based. District wide, surface water provides the majority of water to irrigation demands. However, ground water is the principle source of supply in the populated coastal areas with surface water providing recharge to the shallow aquifers.

Ground water droughts are the result of deficient rainfall combined with a corresponding increase in demands. Qualification of available yield from an aquifer is complicated by the physical constraints which govern ground water occurrence and flow. Therefore, to accurately assess the availability of ground water, a variety of factors including user demands, aquifer hydraulics, recharge, and other natural system losses (regional outflow, leakage, evapotranspiration, etc.) must be addressed either implicitly or explicitly in both spatial and temporal terms. This could be attempted by two approaches: physical flow models or stochastic modeling. The physical model addresses the aquifer hydraulics, demand, and recharge terms explicitly and allows for the calculation of future conditions based on user specified projections of future conditions. Limitations of this approach are that the results are tied to the explicit expressions of the hydraulics and demands. Errors associated with estimates of the aquifer characteristics, boundary assumptions and water use will skew the resulting forecasts.

Stochastic models address the physical parameters implicitly in terms of historical water level data. The idea being that the sum of all the external factors are expressed in an actual water level measurement. Time dependent variables can therefore be addressed through the evaluation of trends in the time series data. A major limitation of the stochastic model is that it utilizes historic data to forecast future trends. Difficulties arise when the existing system is changed (i.e. new wells added, canals or drainage systems added, etc.). Therefore, the ideal approach for assessing and forecasting ground water shortages would utilize features of both stochastic and physical flow models.

PURPOSE AND SCOPE

This purpose of this project is to develop a quantitative approach to the assessment of ground water conditions which could be utilized to support water management decisions associated with the District's Water Shortage Plan.

The result of this study represent the second phase of a four phase system development. The first phase, completed in 1984, involved the quantitative design of a regional monitor network. The second phase involves the development of a multi-variate stochastic model for water level forecast and drought quantification. The third phase will incorporate water use data from the District's Geographic Information System (GIS) currently under development. The GIS data will consist primarily of well location data with seasonal pumpage estimates. This information will be useful in identifying those withdrawals which are influencing regional conditions. The final phase of the system development will involve the incorporation of a regional, three dimensional ground water flow model with the stochastic model. The flow model will be used to evaluate the impacts of different water shortage cutback options prior to implementation.

The approach developed here was designed to address seven goals which were derived from the District's Water Shortage Plan and from discussions with members of the District's water shortage team. These goals are listed below:

1. The model developed should be based on the correlation of dominate variables. Water level and rainfall time series data were used in this preliminary study. The third major variable, pumpage, was not explicitly addressed due to limitations in data availability and reliability which occurred at the time of the study.

2. The model must be capable of dealing with a monitoring network consisting of randomly distributed stations with differing lengths of record.

3. Model results should include comparisons of current conditions to historic water level conditions (maximum, means and minimums).

4. The model should calculate water level return frequencies to provide insight to the severity of current conditions.

5. Forecasts of future water levels should be included. The forecasts should address above average, average and below average rainfall scenarios.

6. Time series data updating should be automated to minimize transposition errors and save time.

7. Output from the model should be accessible to managers throughout the agency in a format which is easy to understand and flexible enough to allow detailed examinations of individual stations as well as summarize regional conditions for entire aquifers.

The model developed in this study is a prototype which was developed specifically for application in Collier County using the U. S. Geological Survey ground water monitor network. The principles which govern this model may be applied to other areas of the District providing a detailed monitor network has been in place for several years. Only water level data were addressed in this study due to limitations in water quality database. This component could be added in the future as more attention is being placed on maintaining water quality monitoring.

DESCRIPTION OF STUDY AREA

Location

The study area consists of the western half of Collier County located in south western peninsular Florida and contiguous portions of adjacent counties (Figure 1). The area is bordered by Lee, Hendry, and Monroe counties and by the Gulf of Mexico to the west. The area is divided into three physiographic regions: the Flatlands, the Big Cypress Swamp and the Ten Thousand Island regions (Davis, 1943). The

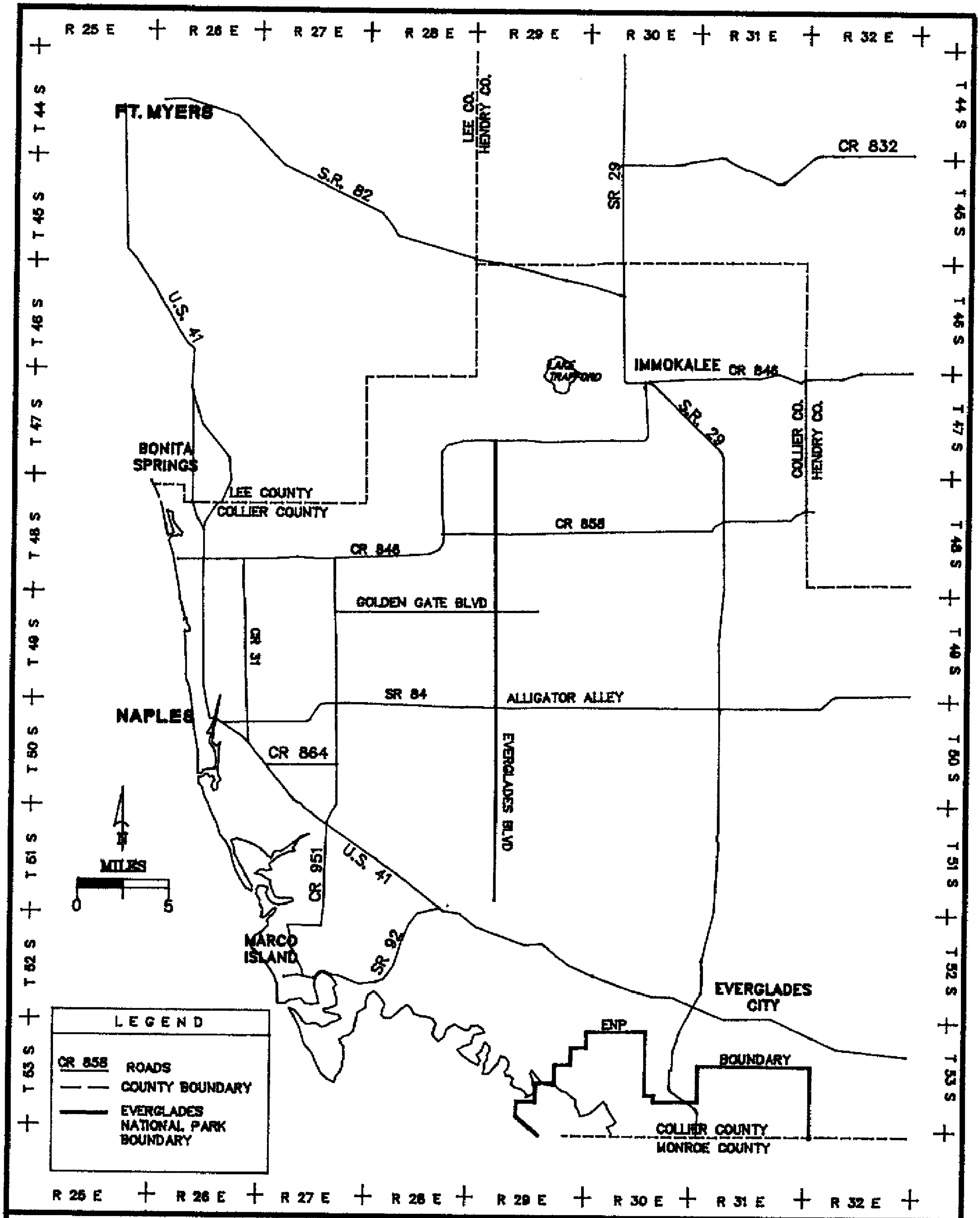

FIGURE 1. LOCATION OF STUDY AREA

Flatlands region occurs throughout the north and western portions of the county. These areas are characterized by moderately drained sandy soils which support most of the agricultural and urban development of the county. The Big Cypress Swamp region occurs in central Collier County and consists of poorly drained muck soils which support extensive wetland systems. The Ten Thousand Island region occurs along the coastline southward from Naples to Monroe County.

Geographically, the county supports two types of development. Urban activities are concentrated within ten miles of the coast from Marco Island through Bonita Springs. The remainder of the county is relatively undeveloped swamp and pine forest.

Hydrogeologic Overview

Ground water used to supply demands comes from three fresh water aquifers in Collier County: the water table, the lower Tamiami and the sandstone aquifers. A fourth aquifer, the mid-Hawthorn, contains water of variable quality and is not developed as extensively in the county. These aquifers are separated from each other by semi-confining beds of low permeability (Figure 2). More detailed descriptions of the ground water resources of the county are described by Knapp et. al. (1986).

The water table aquifer consists of surface sands overlying biogenic sandy limestones. The aquifer occurs throughout the study area and ranges in thickness from 25 to 75 feet. It is generally high yielding (transmissivities between 30,000 to 2,000,000 gpd/ft) except in the Naples area where the unit is thin and composed of fine grained silty sands. Water quality is generally fresh, except along the coastal regions and is characterized by high iron and organic constituents. Despite the generally high permeability of the of the water table aquifer, development is constrained by several factors including: coastal salt water intrusion, wetlands impacts, dewatering, impacts on other users, and potential/actual toxic contamination. As a result, water use from this source has generally been limited to agriculture located in the north central portion of the county.

The base of the water table aquifer corresponds to the first occurrence of low permeability micrites and clays known collectively as the Tamiami confining beds. This unit ranges in thickness from 0 to 75 feet and is considered to act as a semi-confining bed for the underlying lower Tamiami aquifer.

The lower Tamiami aquifer occurs throughout the study area and is the major water producing unit. The aquifer consists of highly permeable biogenic limestones which grade into lower yielding sandstones near the base of the unit. Features that make this aquifer desirable as a source of supply are high transmissivites (averaging 100,000 gpd/ft) good quality water, and the semi-confined nature which allows rapid recharge and some level of protection from surface contamination. Constraints on the availability of water from this aquifer include coastal salt water intrusion, upconing of connate water from the low permeability basal sandstones, impacts on other users, and impacts on the adjacent aquifers caused by leakage.

The lower Tamiami aquifer is the primary source of drinking water in the area with five utilities utilizing this aquifer. In addition agricultural, recreational and private irrigation wells tap this source. The most extensive development of the lower Tamiami aquifer occurs along the coast in the Bonita Springs/Naples area. The magnitude of these cumulative demands in the proximity of the salt water interface

<table>
<tr><th colspan="4">GEOLOGY</th><th rowspan="2">LITHOLOGY</th><th colspan="2">HYDROSTRATIGRAPHY</th></tr>
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<tr><td>QUARTER.</td><td>PLEIST.</td><td colspan="2">UNDIFFERENTIATED</td><td>FINE TO MED QUARTZ SHELL AND SILT; NEAR BASE OF SEQUENCE</td><td rowspan="4">SURFICAL AQUIFER SYSTEM</td><td rowspan="2">WATER TABLE AQUIFER</td></tr>
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<tr><td>OLIGOCENE</td><td colspan="2">SUWANNEE LIMESTONE</td><td>LIGHT ORANGE BIOGENIC CALCARENITE LESS THAN 5% SAND. FORAMS AND ECHINOIDS. MOLDIC INTERGRANULAR POROSITY. HIGH YEILD NEAR TOP AND BOTTOM OF UNIT.</td><td>SUWANNEE AQUIFER</td></tr>
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FIGURE 2. HYDROGEOLOGIC OVERVIEW OF COLLIER COUNTY

has resulted in frequent implementation of mandatory water use restrictions in this area.

A series of Miocene clays and dolosilts form the base of the lower Tamiami aquifer. This sequence of low permeability sediments, known as the upper Hawthorn confining zone, restricts vertical flow to the underlying sandstone aquifer.

The sandstone aquifer is composed of biogenic sandy limestones, dolomites and sandstone. The aquifer is thickest in the northern portion of the study area (averages 125 feet thick) and thins to extinction south of State Route 84 in the central portion of Collier County. As a result, aquifer yield is variable with highest transmissivities in the north (between 50,000 and 100,000 gpd/ft) and decreasing to the south. The aquifer is better confined than the lower Tamiami in most of the study area and recharge rates are comparatively slower. This factor, combined with low storativity of the aquifer, results in large drawdowns of the potentiometric surface near pumpage centers. Water quality is generally very good with isolated areas containing brackish water.

The sandstone aquifer is most extensively developed in the northern portion of the study area. Agriculture is the primary user of the aquifer in this region. The primary constraint on water availability from this source is impacts on neighboring users during extended dry periods.

The base of the sandstone aquifer is defined by a series of green dolosilts and clays known as the mid-Hawthorn confining zone. The thickness of this unit is variable (25 to 200 feet) based on the occurrence or absence of the sandstone aquifer. The mid-Hawthorn confining zone effectively restricts flow between the sandstone and the underlying mid-Hawthorn aquifer.

The mid-Hawthorn aquifer is a low yielding aquifer which occurs throughout the study area. It is composed of sandy phosphatic limestones which exhibit intergranular and moldic porosity. The thickness of the aquifer ranges between 50 and 125 feet, however, most of the flow occurs near the top of the unit. The top of the unit occurs between -300 and -400 feet NGVD.

The potentiometric surface of the aquifer is above land surface throughout the study area, making this unit a possible source of recharge to overlying aquifers. Well yields range between 50 to 150 gpm. Variable water quality, low yields and well construction costs are factors which have resulted in sparse development of this resource.

MONITORING NETWORKS

GROUND WATER

The methodology developed uses monthly ground water and rainfall data as the basis for trend analysis. Other factors which influence ground water levels, pumpage and aquifer hydraulic data, are not explicitly defined in this phase of model development. However, the effects of these factors are inherently expressed in the specific ground water level measurements.

Ground water data is collected monthly from 125 randomly distributed wells covering the four primary fresh water aquifers (Figures 3 and 4). End of month data are collected by the U. S. Geological Survey using hand tapes or digital recorders and stored in their water level database. Additional ground water data are collected by several private utilities and submitted to the District as part of the conditions of their permit. This information has not been included into Ground Water Management Model (GWMANMOD) due to inconsistencies in data and reporting. If this model proves to be an important management tool, guidelines for sampling and reporting could be established which would allow the user collected data to be incorporated into GWMANMOD.

The U. S. Geological Survey monitor network evolved over time as remnants of past localized ground water studies. As a result, the distribution of monitor wells was not regular but skewed towards development centers and sampling frequencies varied with the scope of the original studies as well as subsequent funding. This made it difficult to develop regional ground water resource assessments.

In 1984, Burns and Shih completed a quantitative evaluation of the monitor network in Collier County. Using the uncertainty residuals (variance) resulting from application of a kriging algorithm, the areal significance of the existing well distribution was assessed and recommendations for additions and deletions were made. In addition, time series analyses were conducted on several wells to determine optimum sampling frequencies. Although daily monitoring was necessary for wells located near production wells, it was determined that no less than monthly sampling would be necessary for the development of a forecast model. The recommendations made in this study were implemented in 1986.

The present ground water monitor network is also used to provide water quality data. However, the existing water quality database is not adequate to support time series analysis at this time. This is due to inconsistencies in data collection caused by random sampling frequencies. Development of a structured water quality database is a necessary part of accurate water shortage assessments as saltwater movement is a primary constraint on water availability during droughts. Future revisions of GWMANMOD should be geared towards addressing water quality trends. This will require modifications in the existing water quality sampling program currently in place in Collier County.

RAINFALL

Rainfall is the driving mechanism in ground water supply as it controls both recharge rates and withdrawal demands. Collier County receives an average of 55 inches of rainfall annually (MacVicar, 1983) which is unequally distributed across the area (Figure 5). Rainfall is seasonal with approximately 60 percent of the total occurring during the wet season (June-November). The spatial distribution of

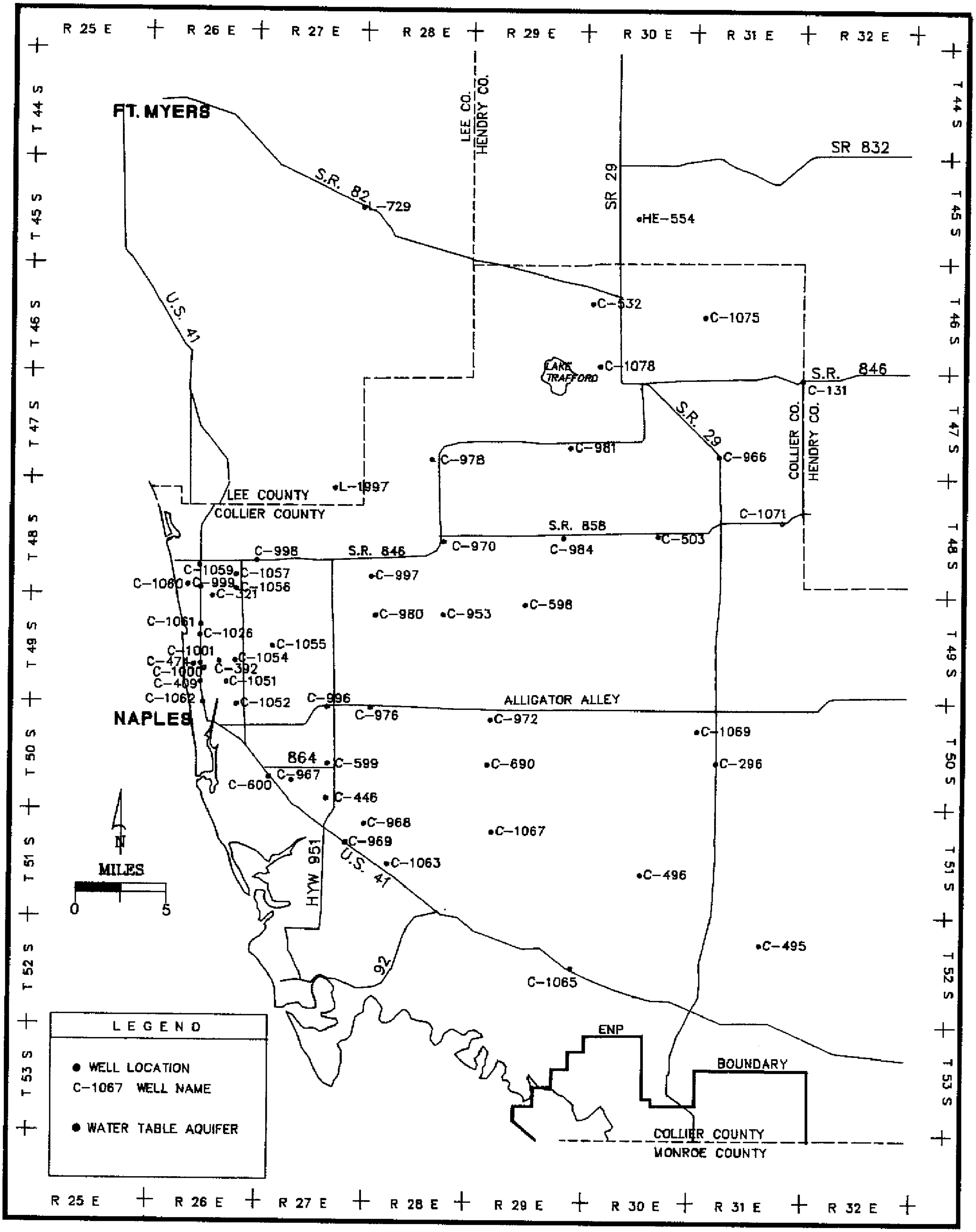


FIGURE 3. LOCATION OF WATER TABLE AQUIFER MONITOR WELLS

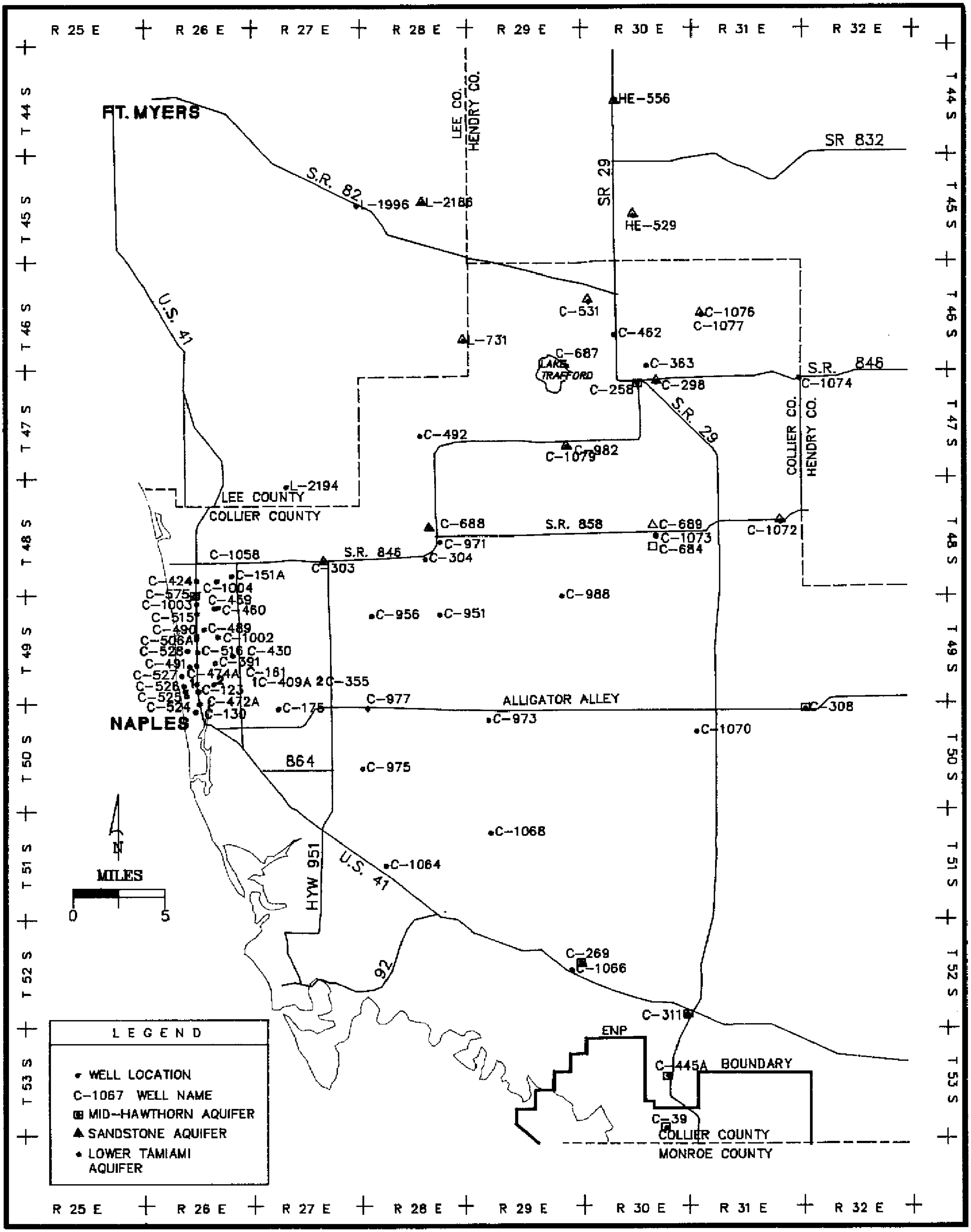


FIGURE 4. LOCATION OF MID HAWTHORN, SANDSTONE AND LOWER TAMIAMI AQUIFER MONITOR WELLS

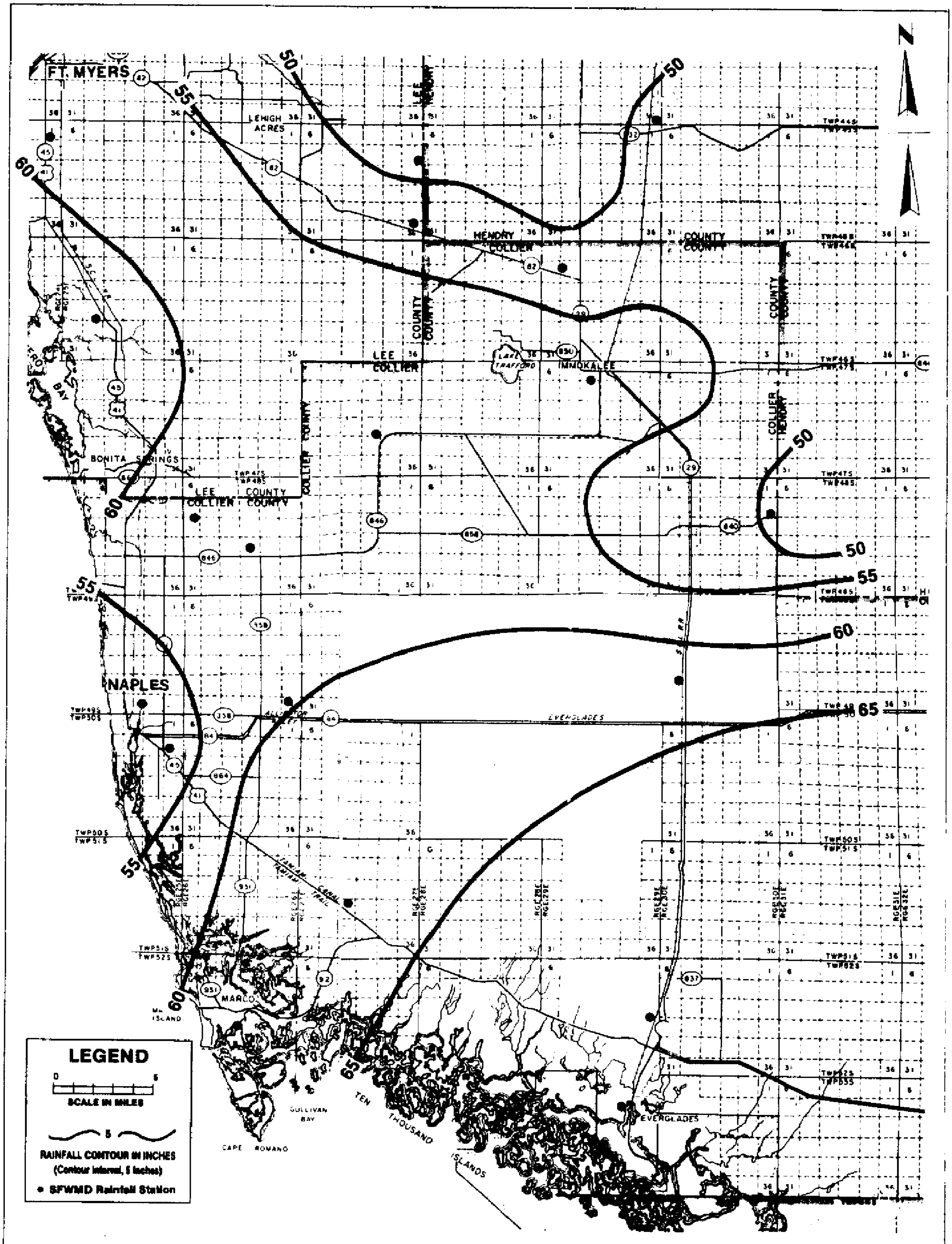


FIGURE 5. AVERAGE ANNUAL RAINFALL DISTRIBUTION FOR THE STUDY AREA

rainfall combined with the seasonal variations in accumulations and climate are principal factors in water availability.

Monthly rainfall accumulations used in GWMANMOD are collected from 13 stations located in and around the study area (Figure 6). These stations were selected based on the length and completeness of record combined with the areal distribution throughout the region. These stations are maintained by NOAA, the U. S. Forestry Service, and various municipalities. Rainfall data are phoned in to the District at the end of each month and stored on the District's hydrologic database (DBHYDRO).

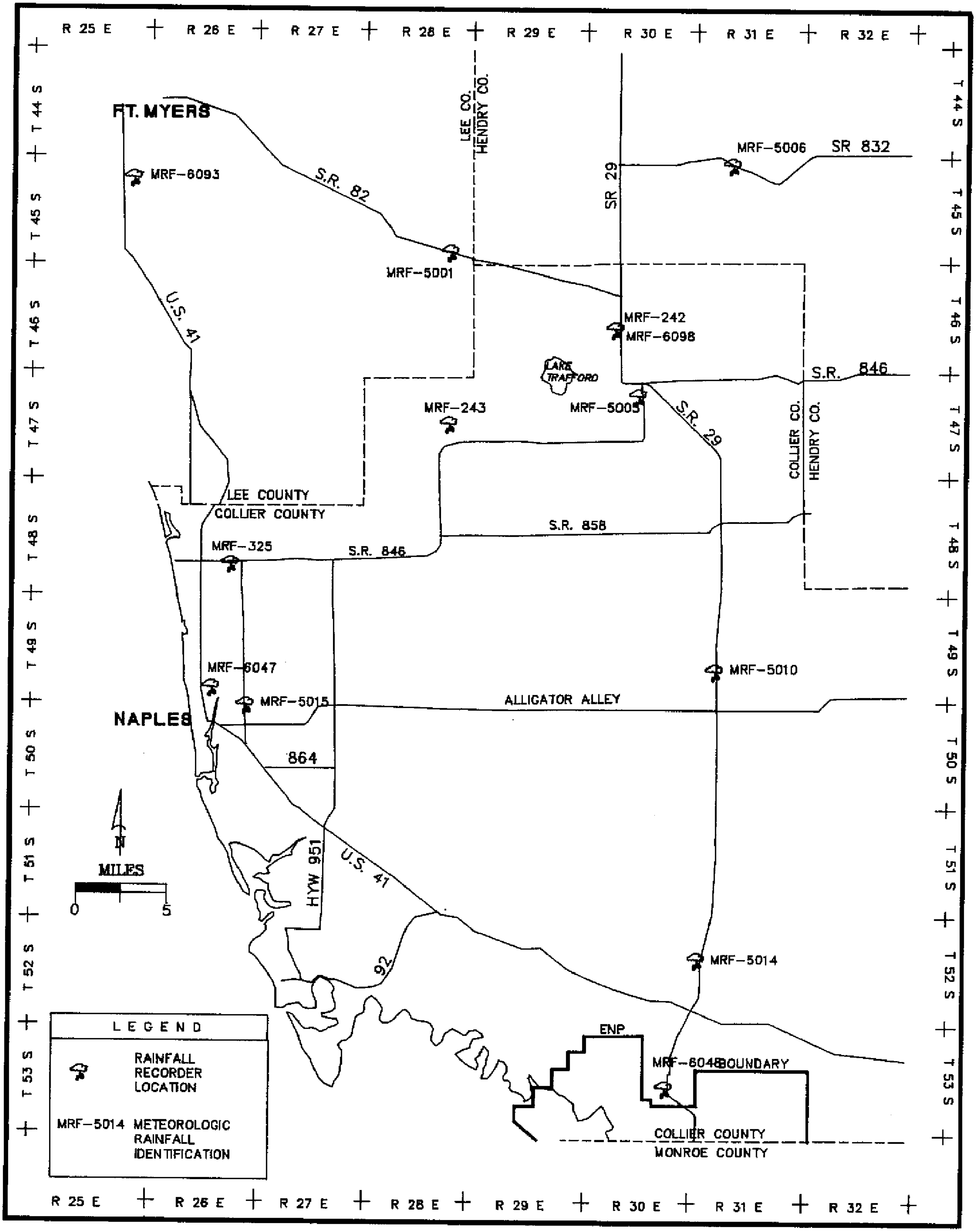


FIGURE 6. LOCATION OF RAINFALL MONITOR STATIONS IN THE STUDY AREA

MODEL DEVELOPMENT

The statistical model developed consists of three components: a) a basic statistical summary, b) water level return frequency analysis and c) water level forecast. These components are presented in a format which allows evaluation of individual well conditions as well as regional trends. The results of the analysis are presented both graphically and numerically as specified by the user through the interactive menu. The types of output available include:

1. Location of monitoring stations for each aquifer,
2. Summary of historical water level data (well hydrographs or raw data reports),
3. Statistics of historical records for each well (maximums means minimums, standard deviations, skewness),
4. Comparison of historic, existing and forecasted water levels to various drought return frequencies,
5. Forecast monthly water levels up to six months into the future,
6. Contours of regional water level trends for historic, existing and forecasted conditions, and
7. Identification of areas of critical concern (wells with water levels below average or below a specified drought return frequency).

BASIC STATISTICS

Both rainfall and ground water data are recorded in the form $Z_{i,j}$; where Z is the data value, i is the calendar year and $j = 1, 2, ..., 12$, is the month of the year. For each ground water station, period of record data are evaluated to produce the following statistics:

1. Monthly mean,
2. Maximum of the month, and the year it occurred,
3. Minimum of the month, and the year it occurred,
4. Standard deviations of each month, and
5. Skew coefficients of each month.

These statistics are helpful for rapid comparison of current and historic conditions. They can be retrieved for individual stations, or incorporated into maps.

WATER LEVEL FREQUENCY ANALYSIS

In order to determine appropriate levels of water use cutbacks, it is necessary to determine the severity of water shortage at any given time. This task is relatively straightforward when dealing with a reservoir of known volume. Under these conditions, constraints on availability are defined by the base of the reservoir or the depth where water can no longer be accessed. Comparisons are made of existing volumes against projected demands over time to determine the probability of meeting the demands before recharge occurs.

With ground water systems, the availability of water is more difficult to define. Factors regarding the hydraulics of the aquifer are mostly unknown and constraints on available yield (adverse impacts on water quality, environment, the aquifer, or other users) vary both spatially and temporally. Physical ground water flow models are capable of estimating these variables explicitly. However, physical models are data intensive and are based on a number of assumptions.

The frequency model applied here is based on the evaluation of historic trends in rainfall and water level data. This type of analysis works well in areas where data trends are relatively consistent. In areas prone to changes in distribution and magnitude of demands, information derived from past trends in water levels will not be adequate for addressing abrupt changes in the system. This is the case in the study area which is one of the fastest growing areas in the nation. As a result, new record low water levels in individual monitor wells may not be indicative of regional drought conditions but instead reflect localized changes in water use. For these reasons, the use of frequency analysis for assessing ground water droughts in this region should not be the sole criteria for assigning mandatory restrictions. It should be used in conjunction with sound professional judgment to determine water management strategies during water shortages.

Drought recurrence probability of existing water conditions is calculated in terms of return year. This information could be generated the following two ways:

1. Compute the percentile location of the current water level reading using historic data collected for that month only. This computation gives the probability with respect to a specific month, not with respect to a year. For example, to classify the return frequency of a water level measured in April, only historic data from the month of April would be used without considering other months of the year. Under this assumption September could have the same probability of being in water shortage as in April, even though there usually is more water in storage in September than in April. Thus, using monthly analysis, if a shortage in an April is at 5% probability, it should be interpreted as an 1-in-20-April shortage, but not as a 1-in-20-year shortage. Probability with respect to a given month is more sensitive to short term deficits in storage which are often averaged over in annual frequency analyses. This is important in south Florida where the most severe droughts may begin in the last months of the preceding wet season.

2. Compute the percentile location of the current water level reading using data collected for all the months in the year. The results will be in terms of "return year". This approach will almost eliminate the paradox of water shortage in September, and concentrate the possibilities of water shortage in the months of the dry season. This is the conventional way of frequency analysis. A recurrence probability of water level is a straight line for the whole year. The disadvantage of this approach is that it can be insensitive to severe warnings that appear near the end of wet season or the early dry season. For example, in October the system usually has ample surplus water in storage; if, in an October, the system has near zero storage because of low rainfall in the wet season, the annual analysis may not show any alarm, even though the conditions could be worse than an 1-in-50 "October" water shortage.

By surveying potential users, most persons felt monthly frequency analysis was more appropriate for south Florida ground water systems than the traditional yearly analysis. Consequently, for a given recurrence probability of water levels, twelve values are calculated in a year. It was further decided that four recurrence frequencies would be calculated for each monitor station for each month. These recurrence frequencies are as follows:

Frequency	Probability
1-in-5 year	20%
1-in-10 year	10%
1-in-20 year	5%
1-in-50 year	2%

Pearson type 3 distribution was selected for use in this study because:

1. The data generally meets the assumptions inherent to this type of analysis,

2. Most of the District's frequency analyses employed this type of distribution, and

3. It fits a wide range of distributions with only 3 parameters.

The distribution is expressed by (Haan, 1977).

$$Z_T = z_m + sZ*K_T \qquad (1)$$

Where Z_T is the magnitude of low water level in 1/T recurrence probability; z_m is the mean of the sample; sZ is the standard deviation of the sample; and K_T, available in table form, is the frequency factor as a function of recurrence probability and the sample coefficient of skewness, C_s.

$$C_s = n\, sum\, (z - z_m)^3 / \{(n-1)(n-2)^* sZ^3\} \qquad (2)$$

Where n is the number of samples, or one half of the number of years in the records of a station, and z is the water level of the month which is less than the mean of that month.

The statistics, such as z_m, sZ, and C_s, for each station, are calculated from the historical data and are included in the model output. In some cases, Z_T is given as current status, while 1/T, the recurrence probability, is being sought. The procedure was reversed as follows to approximate T:

1. Compute $K'_T = -(z_m - Z_T)/sZ$ (3)

2. Linearly interpolate T for K'_T with the given C_s taken from the table.

The results of the frequency analysis are displayed both graphically and as raw data. Because of short records in some stations, these line segments may not connect up to form smooth curves.

WATER LEVEL FORECAST MODEL

Box and Jenkins (1976) ARIMA modeling techniques were selected for the development of the forecast models. An independent model was developed for each ground water station using a two phase approach. First, a univariate model was built for each rainfall station. Next, a transfer function model, using rainfall as stochastic input variable, was developed for each ground water station. Software packages to perform the time series analysis are available in BMDP (1985), SCA (1985), and Statgraphics (1986).

Model Identification

The purpose of model identification is to define a subclass of models to investigate some phenomena in detail. The basic process is to examine the auto-correlation function (ACF) and partial auto-correlation function (PACF), or cross-covariance functions of the related series. Particular patterns of these functions suggest the probable model structure. This is a time consuming visual examination process. In order not to overlook any potential model, a large class of tentative models were examined for each time series. Later, these models were scrutinized among comparable time series to eliminate some of the higher order models that occurred only in a single time series.

Estimation and diagnostic checking, mostly computerized, followed the iterative procedures employed in the computer packages. Conditional least square and backcasting methods were selected for parameter estimation. Diagnostic checking followed the similar procedure of examining the ACF and PACF of the residuals. t values greater than 2.0 were used to eliminate insignificant parameters. Ultimately, the standard error of the forecast was used to make the final model selection.

Rainfall Modeling

Rainfall is the replenishing source of ground water and therefore, a good indicator of future ground water levels. Ground water fluctuation generally follows rainfall, hence current and past rainfall can be used as predicting variables for future ground water levels. In many cases, however, to forecast ground water level, rainfall may also have to be forecasted. This is the case when rainfall data is not reported or during forecasting. The use of model forecasted rainfall will improve the forecast reliability. Since no other monthly rainfall forecast mechanism was readily available, uni-variate time series analysis was used to build stochastic models for rainfall forecast. The applicability of ARMA models for rainfall forecast relies on the fact that there are strong yearly patterns and some less significant multi-year cyclic behaviors in south Florida rainfall (Shih, 1987a).

There are 13 rainfall stations with continuing records updated monthly in the area. An average rainfall series is also computed from these 13 stations. Therefore, a total of 14 time series are available as stochastic input variables for the model development.

It was assumed that rainfall time series were stationary, hence ARMA was appropriate. The general form of uni-variate ARMA model is:

$$P(B)y_t = Q(B)a_t \qquad (4)$$

Where y is the monthly rainfall, a is the shock noise, and the subscript $_t$ denotes the time. The model structure is presented in the polynomials P and Q.

$$P(B) = (1 - p_1B - p_2B^2 - \dots - p_pB^p) \tag{5}$$

$$Q(B) = (1 - q_1B - q_2B^2 - \dots - q_qB^q) \tag{6}$$

B's in equations (5) and (6) are back shift operators such that

$$By_t = y_{t-1} \quad or \quad B^q a_t = a_{t-q} \tag{7}$$

and p_i, $i = 1,\dots p$ and q_j, $j = 1,\dots q$ are model parameters.

A multiplicative model was used to represent seasonality for parameter parsimony.

$$P(B)P_s(B^s)y_t = Q(B)Q_s(B^s)a_t \tag{8}$$

Where P_s and Q_s are polynomials similar to P and Q for describing the seasonal structure of the model.

During the model identification process, probable models of each series were recorded in ARMA(P,Q) notation while observing ACF's and PACF's. The symbols, P, and Q are factors and orders of autoregressive, and moving average components, respectively. Each order was expanded to include lags and association of multiplicative factors for a clear model presentation readily adaptable to the selected computer package. Tentative models were calibrated to produce the residual information for model improvement. This iterative process was repeated until at least a satisfactory model was identified for a rainfall station. After eliminating duplicated models, nine potential models were identified, six of which were multiplicative models.

In parameter estimation, each rainfall data point was considered to have equal weight. Not all the p_i and q_j were necessarily significantly different from zero. The significance of the parameter coefficients were discriminated by t values. It appeared that a common pattern or physical structure was governing the rainfall in the area. Therefore, parameter estimations were attempted for each rainfall series using all the nine tentative models. Hopefully, by this trial of multiple models, it would be possible to correct any mistake in the model identification of each time series, and provided one more dimension of freedom for the rainfall models to seek their commonality. The calibrated models were used to compute forecasts and the forecast errors. The final models selected were the ones which produced the minimum forecast errors. Not surprisingly, the majority of models converged to ARMA (1,1) with lags at 12 reflecting strong yearly cycles.

Ground Water Modeling

A transfer function was used to model ground water levels because of the fast availability of current rainfall data. The transfer function model is a special case of multi-variate models where input variables (rainfall) are affecting the output variable (ground water levels), while ground water levels are not affecting rainfall. The uni-directional nature of this relationship makes it feasible to apply uni-variate model building techniques to this type of multi-variate model.

The transfer function model identification procedures used are outlined by Box and Jenkins (1976). First, a model is built for prewhittening the rainfall input. Note that the prewhittening model may not be the same as the one previously identified for forecasting purposes. The model is used to transform the correlated input (rainfall) variable into uncorrelated white noise. The same model is also used to transform the ground water (output) series into another series. Then the cross covariance function between the noise series from transformed input series and the transformed output is computed. The cross covariance function was the primary information to help "guess" at the transfer function model structure.

It was assumed that ground water series were stationary and that no differencing was necessary. However, the latest ground water trend was emphasized by weighting factors and monthly model parameter up-date, which will be discussed later. A transfer function model takes the form:

$$P(B)z_t = Q(B)y_{t-b} + R(B)a_t \qquad (9)$$

Where z is the ground water level, y is the rainfall, and the orders of P and Q are p and q, respectively. In addition, b is the pure delay of the output response to the input, and R(B) is another polynomial of back shift operator B. The z_t term can stand alone in the left-hand-side of equation (9) by dividing the right-hand-side of the equation by P(B) to become:

$$zt = v(B)y_t + N_t \qquad (10)$$

Where v(B), the impulse response function, is a polynomial of B, and N_t is the residual series.

Suppose it is possible to use the model $R_y(B)S_y{}^{-1}(B)$ to reduce the input y_t into white noise, A_t:

$$R_y(B)U_y{}^{-1}(B)y_t = A_t \qquad (11)$$

Where, again, R_y and U_y are polynomials, and the superscript -1 denotes the inversion. Then, the same model is used to transform the output z_t into yet another series, G_t:

$$G_t = R_y(B)U_y{}^{-1}(B)z_t \qquad (12)$$

then,

$$G_t = v(B)A_t + E_t \qquad (13)$$

Where

$$E_t = R_y(B)U_y{}^{-1}(B)N_t \qquad (14)$$

The cross-covariance function, C, at lag +k between A and G is obtained by multiplying both sides of equation (13) by A_{t-k},and taking the expectation:

$$C_{AG}(k) = v_k S\,{}^{-}{}_{A}{}^{2} \qquad (15)$$

Where ${}^{-}{}_{A}{}^{2}$ is the variance of A_t. The cross-covariance function is the primary information to guess at p,q and b in equation (9). Similarly, to identify the noise model for N_t, the autocorrelation function for E_t is computed from equation (14). Again, the display of those functions was inspected to derive the probable model structure.

The information provided by the cross-covariance and the autocorrelation function was very sketchy making it difficult to identify a transfer function model. As suggested by Box and Jenkins (1976), a second order (three-terms) polynomial for P and Q is usually sufficient for most application models. Therefore, the output function P was limited to less than three terms, and the input function to be less than five terms, including the pure delay and the multiplicative factor for seasonality. In addition, the noise model was constrained to less than three-terms with heavy use of a multiplicative factor for parameter parsimony. However, high orders of backshifts were accepted to use past information as much as possible for the forecast and to capture the long cyclic messages.

There are 125 ground water stations in the study area. To search for the tentative transfer function models, each ground water station was paired with the nearest rainfall station by visual inspection. It is possible that pressure heads in confined aquifers may not readily respond to local rainfall. However, average rainfall series were assigned to all stations that were monitoring confined aquifers. Following the identification process outlined previously, approximately 200 potential models, or about 1.5 models per series, were identified. After eliminating the duplicated models, the number of potential ground water time series models was reduced to 58.

In the previous identification process, rainfall series were arbitrarily assigned to a ground water station based on distance. The influence of different rainfall input to the result of the identified model(s) for a ground water station was also examined. Not surprisingly, the best rainfall station for the forecast of the ground water levels is not necessarily closest to each other. Forecast improvement of up to two folds were observed. Conversely, a model type identified for a ground water station using the nearest rainfall station as an input variable is not necessarily the best model when combined with other rainfall stations as input. Since the model identification process was very much guess work, it was necessary to test all model types and all rainfall stations during model selection.

Theoretically, up to 14 rainfall series could be used as input variables, however, the number of possible combinations of arrangements become impractical. Considering that rainfall data are correlated, only marginal improvement of model performance could be expected by including a second or third rainfall station. In fact, in a test of three series, after the best rainfall station was selected, the inclusion of a second station did not improve the forecast error by more than 15 percent. As a result, it was decided that only one rainfall station would be used for a ground water modeling. Even with this simplification, for each ground water station, the best forecast model was selected from the comparison of 812 models.

In model estimation where model parameters are calibrated, the data points were weighted to emphasize the latest data and to capture the latest trends. The weighting factors (W) basically follow an exponential function modified with the last 12 points (one year) of data all weight 10.0, and all the data more than 36 years ago weight 1.0.

$$W = 1. + 9. * Exp(-H/111)**2 \tag{16}$$

The justification for such a wide range of weight variation is that the ground water in the study area are under accelerated development in recent years. Hence the ground water levels are going through different rates of decline. Rather than using high order differencing to achieve stationarity, it was decided to couple exponential weights with simpler ARMA models. In addition, the older data contained several omissions which were estimated using backcasting methods to complete the data series. For this reason, much of the older data is less reliable than the more resent readings. While differencing may compound the hidden traps in forecasting, the weighting scheme used here may actually circumvent the problem.

The final forecast model was selected based on forecast error. There is, however, no way to prove that the model is the best available for forecast. Among different models (58) and input rainfall series (14) of a given ground water station, the forecast error often varied over an order of magnitude, while the errors of the best five models were varied within 10%. Based on the small error eventually achieved, the selected models are considered to be near optimum.

The model is automatically re-calibrated every time new data is added to the time series. This automatic model up-dating, immediately incorporating all the information of new data, is particularly helpful for stations with short records. The modeling system is set up such that the forecasts are done to a given month at all stations regardless of the data availability. The rainfall input is considered to be stochastic so that the reliability (variance) of rainfall forecast is considered in the ground water level forecasts. The forecast values and their standard errors are incorporated into various hydrograph, recurrence frequency and mapping displays.

MAPPING

To achieve the water shortage description required by the plan, the current and forecast sets of ground water levels, in terms of either elevation or recurrence probabilities, are plotted on a map. These data are available at irregularly located points in space. The point data, in general, are of different reliability. These problems associated in the mapping process are taken care by kriging techniques. Commercial packages (SURFER,1987, Golden Software Inc.) are available for the mapping purpose. This section explains the basic formulation of kriging by following Skrivan and Karlinger (1980).

In time series analyses, locations of gaging points are not specified because this information is not used. To consider the areal distribution of the known values, it is necessary to locate those gaging stations on a map or coordinate system. Let (X_i,Y_i) denote the coordinates of the measuring or forecasting point for variable Z_i. The value at the location i at time, $_t$,is denoted by Z_{it}. Analogous to temporal analysis, which attempts to estimate unmeasured future values at a fixed point in space for instants in time, spatial analysis attempts to estimate unmeasured values in space at a fixed instant in time.

Hand contour mapping is the common method used to extend point data into areal information. The basic assumptions are:

1. The variable to be mapped is continuous, and
2. The sampled point values are equally important, or reliable. Some geo-statistical computer mapping programs, such as kriging do not need the second assumption.

Kriging takes into account:

1. the variance or reliability of measured point data,
2. the growth of variance, i.e. the decay of reliability, as point data are extended away from the measured point, and
3. the relative locations among the measured and unmeasured points by a covariance matrix.

Consequently, kriging cannot only compute every unmeasured (grid) point in the area, but can also give the variance of each estimation. The results can be plotted as the contour map for the variable of concern or the variance distribution showing the reliability of the contour map.

In most cases, a known value for a time variable is actually measured in the field. The variance associated with this kind of measurement, usually attributed to the measurement instruments and procedures, is often considered negligible by default. When "known" values are obtained from statistical methods, they can have a wide range of estimation variances. A large variance reduces the reliability of the measured value, hence the value is "weighted" less in kriging. Only when a known value has a zero variance, is the kriged value exactly the same as the given value; otherwise the kriged value can be either lower or higher than the given value. In most commercial packages, however, the variances at known points are neglected.

A semi-variogram is an equation that relates the growth of estimation variance as a function of distance. In the simplified isotropic, nondrift case the raw semi-variance is computed from the measured values by:

$$G(h_k) = \frac{1}{2*N(h_k)} \text{ sum of } (z_1 - z_2)^2 \qquad (17)$$

Where h denotes distance, k is an integer and $N(h_k)$ is the number of data pairs of data points with distance around h_k. Semi-variance is named from the fact that it is one half of the variance between pairs of given values. The raw semi-variance is then fitted into some permissible function, using G and h_k as variables. The fitted function is called a semi-variogram. For simplicity, most commercial package uses linear function,

$$G(h) = a + bh \qquad (18)$$

where a and b are coefficients calibrated from regression analysis. The upper limit of G(h) is called the "sill", and is denoted by G_0. Equation (18) is used to construct the covariance matrix of the measured and unmeasured points.

Kriging is a method to estimate the value Z at any grid point, $_k$, at the coordinates (X_k, Y_k), from irregularly located given points, by linear combination of the given values z_i.

$$Z_k = \text{sum of } w_i * z_i \qquad (19)$$

where w_i and Z_i are weighing factors determined by conditions of unbiasedness and minimum variance. A system of linear equations is derived by taking the partial derivative of the expected variance with respect to each of the w_i, and setting this derivative to zero to obtain the minimum, and applying constraints of the unbiasedness for the location functions, f_j, by Lagrange multipliers, u_j. The result, in matrix form,is:

$$\underline{P} * \underline{W} = \underline{B} \qquad (20)$$

Where $\underline{P}$ is a $(N+D+1) \times (N+D+1)$ matrix that is symmetrical with respect to the diagonal, and D is the number of monomials for large scale drift, or trend, as a function of location. The first row of $\underline{P}$ is:

$\{(e_1+G^0)\ G_{12} \ldots\ldots G_{1N}\ 1\ f_1(X_1,Y_1)\ f_2(X_1,Y_1) \ldots f_D(X_1,Y_1)\}$;

and the transpose of the last column is:

$\{f_D(X_1,Y_1) \ldots f_D(X_N,Y_N)\ 0\ 0 \ldots. 0\}$, with D number of zeros at the end. The covariance, G_{ij}, between points i and j, is computed by:

$$G_{ij} = G^0 - G(h_{ij}) \qquad (21)$$

and functions, f_d, $d = 1, \ldots D$, are in the form of X^aY^b, where a and b are identified in trend analysis. The vector of the unknown variable, $\underline{W}$, is composed of kriging weights, w_i, $i=1,2,\ldots N$, and the Lagrange multipliers, u_j, $j=0,1,2,\ldots D$, for unbiasedness conditions. The transposed vector on the right-hand-side of equation (16) is:

$\{G_{1k}\ G_{2k} \ldots G_{Nk}\ 1\ f_1(X_k,Y_k) \ldots f_D(X_{k,yk})\}$,

expressing the covariances between the unmeasured and measured points and the location function of the unmeasured point,k.

The kriging variance, G_k, for the estimated value at point (X_k,Y_k), which is the minimum variance for the linear model of equation (19), is

$$\begin{aligned} v_k = {} & G^0 - \text{sum of } w_i{*}G_{ik} - \text{sum of } u_j{*}f_j(X_k,Y_k) \\ & + \text{sum of } w_i^2{*}e_i \end{aligned} \qquad (22)$$

Note that v_k is independent of z_i.

After all the grid point values are computed by the kriging method, the computer package continues to construct the contour lines. Given a contour value, the program computes the locations of the contour line by linear interpolations. Because of many simplifications in the previous processes, the resultant contour lines may not be smooth and show numerous "kinks". To improve the graphical display, a polynomial smoothing function is available at operator's choice. Satisfactory maps are stored for quick regeneration on screen.

DATA PROCESSING

The statistical procedures described above along with the associated data processing routines are incorporated in the software program known as GWMANMOD (Ground Water Management Model). This program is run monthly on a central processor and the results are sent to the District file server where they can be accessed by anyone wishing to determine the status of ground water in the study area. Software is available for installation on any networked PC which will allow the user to operate the post processor. A flow diagram of the system software is shown on Table 1.

Input data necessary to run GWMANMOD consists of end of month ground water level and rainfall accumulation data. The ground water data is collected by the U. S. Geological Survey and stored on the Water Quality/Random Water Level Database. This database resides on the USGS mainframe computer located in Miami. District access to this system is accomplished through a direct data communication line established between agencies. End of month readings are usually available on this database within five days of the original measurement. This data is retrieved and reformatted through the COLICO program.

Monthly rainfall accumulations are phoned into the District's Data Management Division where it is stored on the hydraulic database DBHYDRO. Data is retrieved and formatted from this database through the CRF program.

The two resulting files, which become the input data sets for the statistical model, are CGW and CRF. The output files from the model are PFCFST (the forecast data) and HMLSTAT (the statistics and drought frequency data). These four files form the core of the post processing routines.

The post processing routines are a series of user friendly, graphic display options which are geared toward use by both technical and managerial personnel. User specified output options are categorized into three components: data reports, which consist of raw data tabulations, hydrographs, which display both historic and forecasted water level data for individual wells (Figures 7 and 8), and regional maps which show existing or forecasted water level trends by aquifer (Figures 9 and 10) and level of drought in terms of return frequency.

Under the data report option, the user can retrieve all information pertaining to the monitor network. Because the complete information for all stations is voluminous and difficult to digest, a summary of current conditions compared with historic extremes is provided as an option for the user. All the monitor wells are grouped based on their relationship to the monthly averages. Well data is presented in ascending numerical order by aquifer. Data presented under this option includes date and level of the most recent sample, the average water level for that month, the deviation from the monthly average, the lowest recorded level for the month, and the deviation from the lowest value. Users wishing additional information such as period of record data or drought analysis and forecasts can retrieve the CGW and HMLSTAT files directly.

Users wishing detailed information for individual stations can select the hydrograph options. Depending on the option selected, the program will generate graphs for both historic levels (previous 12 months) and forecasted (6 months in the future) along with either the monthly maximum, minimum, and means, or the

TABLE 1
DATA PROCESSING FLOWCHART FOR GWMANMOD

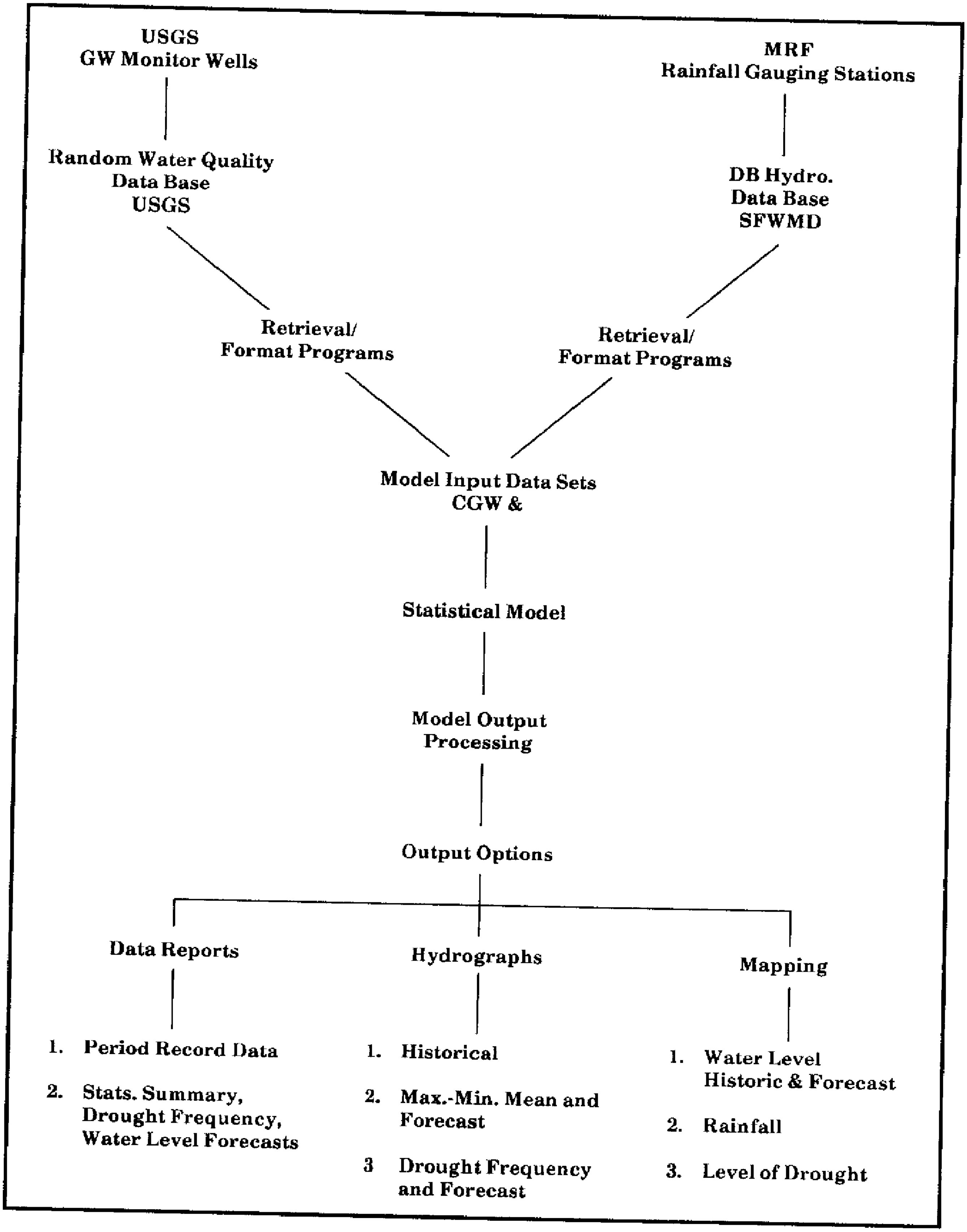


FIGURE 7. COMPARATIVE HYDROGRAPH FOR WELL L-1691; HISTORIC TRENDS PLUS FORECAST

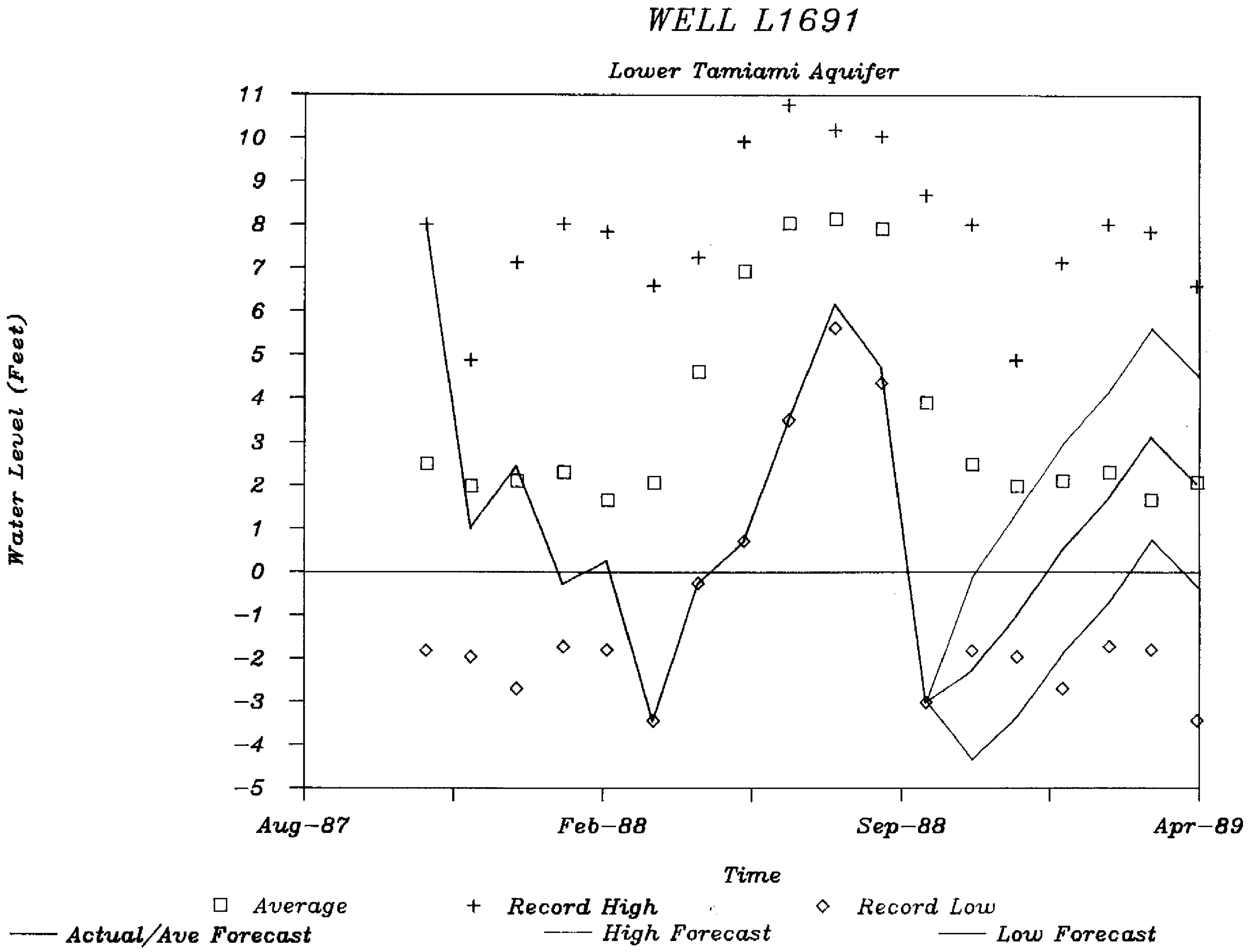
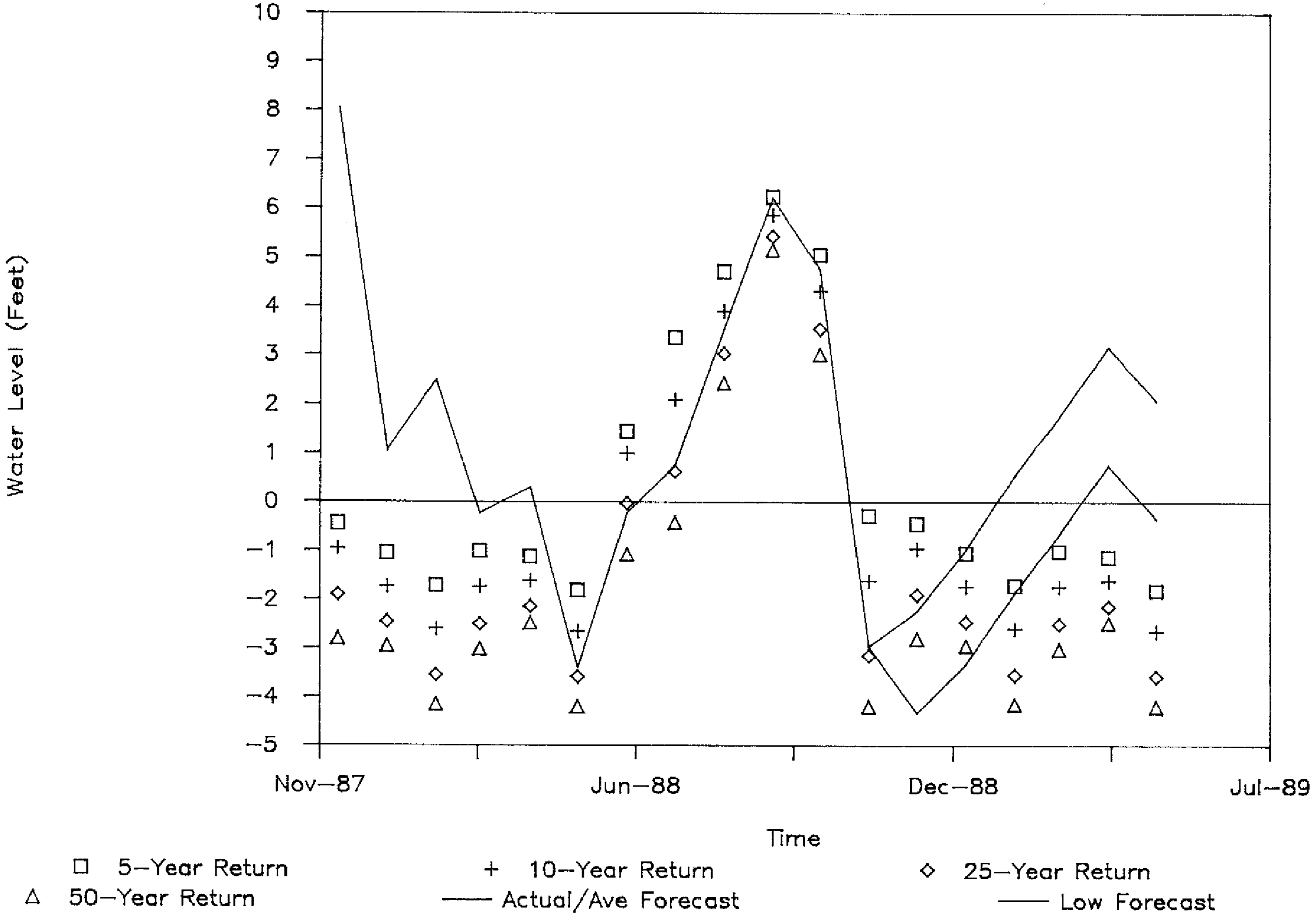


FIGURE 8. COMPARATIVE HYDROGRAPH FOR WELL L-1691; REOCCURRENCE FREQUENCY PLUS FORECAST



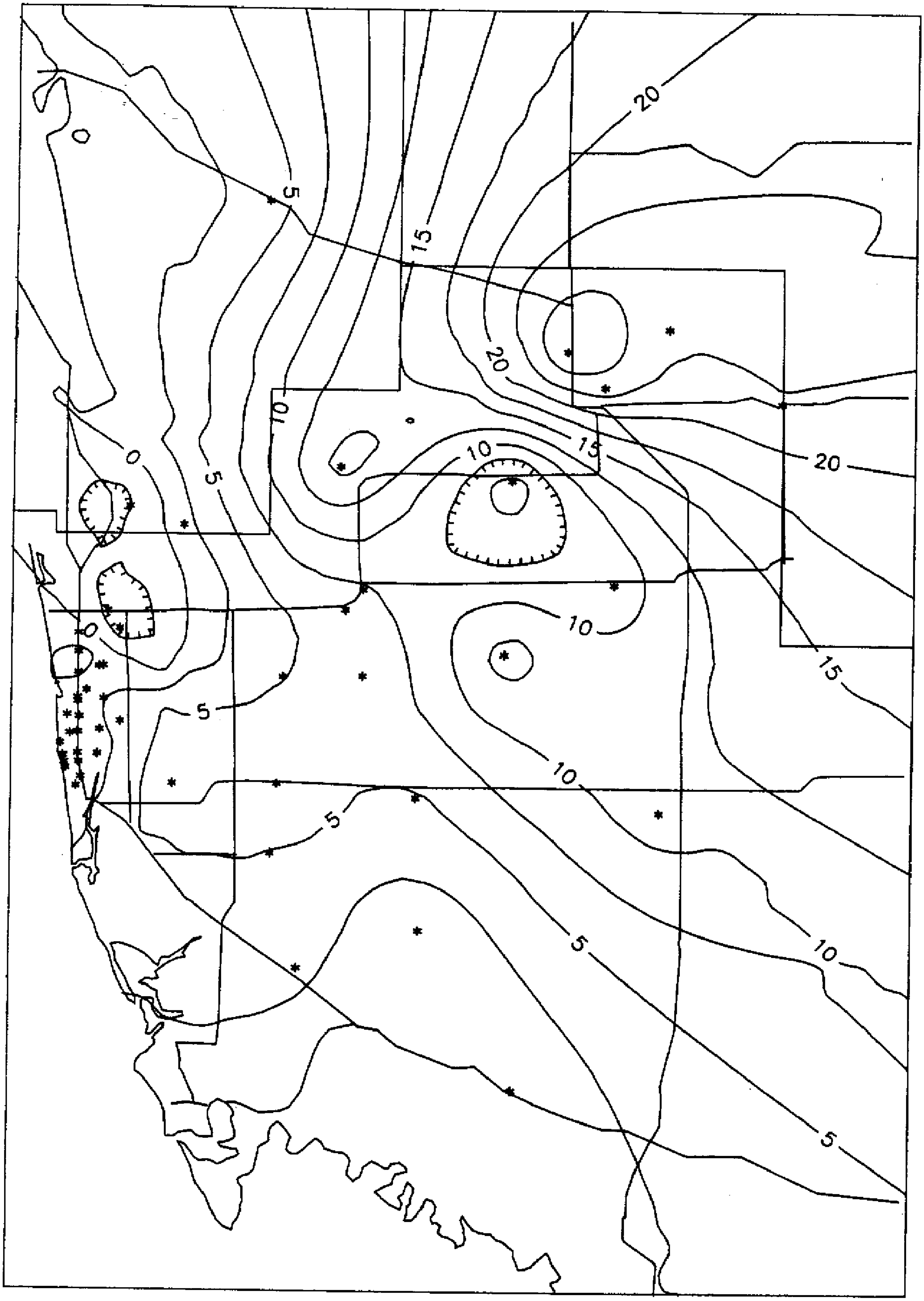


FIGURE 9. WATER LEVEL CONTOUR MAP FOR LOWER TAMIAMI AQUIFER; FORECAST NOVEMBER 1988 DATA

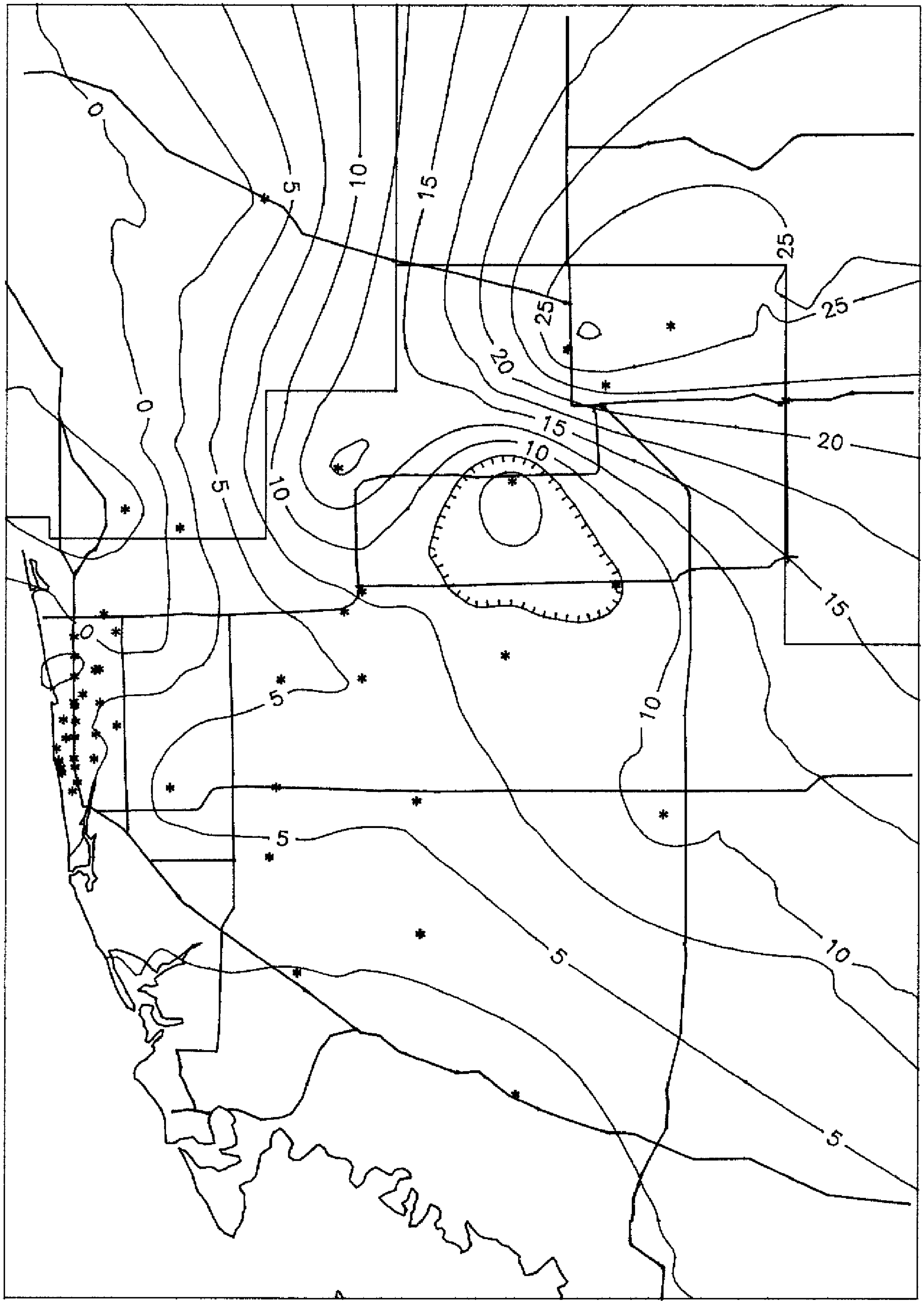


FIGURE 10. WATER LEVEL CONTOUR MAP FOR LOWER TAMIAMI AQUIFER; ACTUAL NOVEMBER 1988 DATA

monthly drought return frequency levels. Graphs can be displayed either on the screen, printer or plotter.

Regional trends are developed by kriging historic or forecasted water level data. In addition, drought return frequencies are mapped to help identify areas of extreme ground water deficits. Due to data requirements of the kriging algorithm combined with limitations in the data network, regional trend analysis can only be performed on the water table and the lower Tamiami aquifers.

CONCLUSIONS

1. A data analysis system (GWANMOD) has been developed for evaluating rainfall and ground water data in order to support water shortage management decisions. The methodologies developed as part of GWMANMOD provide information regarding the degree of ground water shortage (in terms of return frequency), identifies areas where ground water shortage conditions may appear, and provides forecasts of future conditions based on historic trends.

2. Ground water recurrence frequency calculations are based on the application of Pearson Type 3 distribution to historic end of month water level readings. Recurrence frequencies are calculated for each month of the year which provides early indications of short and long term deficits in ground water storage. This method of analysis requires at least six years of data.

3. Forecast models were developed using multi-variate, transfer function models which identify and forecast trends based on rainfall and correlated ground water level time series data. The transfer function models were selected by specifying the model structure for each ground water station. Each model was selected from a large family of tested models based on the minimal resulting forecast error. The coefficients of the forecast models are up-dated as soon as new data becomes available. This self calibrating process is automated within the program.

4. Identification of stressed areas is accomplished by mapping recurrence frequency data and existing and forecast water levels for each aquifer. Regionalization of point data is accomplished through a kriging algorithm available from a commercial software program. This type of display is useful for presenting information rapidly over a large area.

5. There are two major limitations associated with the methodologies developed in this study. The first is that there is no explicit expression of the constraints on availability of ground water in the approach. The model identifies and quantifies levels of stress based on historical data and is not resource based. The next generation of GWMANMOD should incorporate information on resource availability in terms defined in state water use policy. The second limitation in this approach is that the study area is under large scale expansion. The stochastic methods used are based on historical trends. The addition of new wells or increased withdrawals will produce result which are not indicative of regional conditions. Therefore, it is necessary for the user to distinguish actual water shortages from changes in demands prior to making management decisions.

RECOMMENDATIONS

1. Results from GWMANMOD should be incorporated within the District's existing water shortage decision framework to support management decisions. Managers should be aware of the assumption and limitations inherent to this type of statistical analysis and incorporate model results with sound professional judgment.

2. The methodology used in GWMANMOD utilizes time series data which is spatially dependent. Changes in the existing monitor networks will significantly impact the accuracy of the model. Therefore, it is recommended that the existing network be maintained including the continued support of data collection activities and replacement of destroyed wells.

3. In order to more directly assess the availability of ground water during droughts, additional work is needed to define the constraints on aquifer yield. This additional work should be focused in two areas: physical flow model development and dynamics of saltwater migration. The first area is currently being developed as part of the District's water supply planning activities. To determine the dynamics of saltwater migration, a regional saltwater intrusion monitor network should be designed and maintained for both confined and semi-confined aquifers.

4. Water use information should be incorporated into GWMANMOD to improve the efficiency and equity of water cutback decisions. The information needed should include: source of supply, location of withdrawals, type of use, and estimates of amounts and times used. The information should be in a GIS format to facilitate rapid graphical analysis. This information is currently being compiled in the Water Use Division of the Regulation Department.

5. The methodologies developed in this study should be expanded to all coastal counties of the District. Monitor networks suitable to support this type of analysis already exist in all coastal counties except Martin and St. Lucie. However, expansion of these deficient monitor networks are being undertaken as part of existing studies.

REFERENCES

BMDP Statistical Software Manual, W.J. Dixon, Chief Editor, University of California, 1985.

Box, G.P. and G. M. Jenkins, 1976. Time Series Analysis--Forecasting and Control, Holden-Day.

Burns, Wm. Scott and George Shih, 1984. Preliminary Evaluation of the Ground Water Monitoring Network in Collier County, Florida, South Florida Water Management District Technical Memorandum.

Davis, John H., Jr., 1993. The Natural Features of Southern Florida, Especially the Vegetation and the Everglades, Florida Geological Survey Bulletin 25, 1943.

Haan, C.T,m 1977. Statistical Methods in Hydrology, The Iowa State University Press, Ames, Iowa.

Knapp, Michael P., Wm. Scott Burns, and Timothy S. Sharp, 1986. Preliminary Assessment of the Ground Water Resources of Western Collier County, Florida, South Florida Water Management District Technical Publication 86-1.

MacVicar, Thomas K., 1983. Rainfall Averages and Selected Extremes for Central and South Florida, South Florida Water Management District Technical Publication 83-2.

The SCA System, Scientific Computing Associates, Dekalb, Ill. January, 1985.

Shih, G., 1987a. System for Forecasting Drought Progression in South Florida, Presented at International Symposium on Forecasting, Boston, May 26-29, 1987a.

Shih, G., 1987b. Mapping of Drought Status in South Florida, Proceedings, ASCE National Conference on Hydraulic Engineering and Engineering Hydrology Symposium, Williamsburg, Virginia, August 3 - 7.

Skrivan, J.A. and M.R. Karlinger, 1980. Semi-Variogram Estimation and Universal Kriging Program, U. S. Geological Survey WRD-WRI-80-064, Tacoma,Washington, NTIS: PB81-120560.

SURFER, Golden Software Inc., 1987.

South Florida Water Management District, 1986. Water Shortage Management Manual, West Palm Beach, Florida.

STATGRAPHICS, 1986, Statistical Graphics System.