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PART 1 - SALINE CONTAMINATION OF A LIMESTONE AQUIFER BY CONNATE INTRUSION IN AGRICULTURAL AREAS OF ST. JOHNS, PUTNAM, AND FLAGLER COUNTIES, NORTHEAST FLORIDA

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ABSTRACT

St. Johns, Putnam, and Flagler counties are located in northeast Florida within the St. Johns River Valley. The topography is generally flat, and the climate is humid subtropical with a mean annual rainfall of approximately 53 inches. With these conditions, the agricultural production of fall and winter vegetables is a large part of the area's economy. Irrigation for crops begins in late September and continues through May. Intense seasonal ground water withdrawals in several agricultural areas produce cones of depression in which water levels in artesian flowing wells may drop in excess of 20 feet below land surface, and water quality deteriorates severely.

From land surface to more than 200 feet in depth at some localities, the geology of this area consists of sand and clay mixed with thin beds of limestone and phosphate. The Floridan aquifer, which consists of Eocene limestone and permeable basal limestone beds of Miocene Hawthorn Formation, underlies these materials. This aquifer is the primary source of water for irrigation supplies.

From the geophysical logging of 82 irrigation wells, most of the flow zones in the Floridan aquifer were encountered in the upper 50 feet of the limestone. Water samples taken from the deep artesian wells showed that water quality deteriorates as relative depth into the limestone increases and, in some cases, bottom samples exceeded 3,000 parts per million chloride. During times of extended pumping in the agricultural areas, the upconing of deep saline water in the Avon Park formation into shallower fresher zones of the Floridan aquifer has the potential to contaminate other wells in the same general area. Also, many of the old wells which were constructed during the time of higher potentiometric levels act as direct conduits for contamination of fresh upper zones.

Throughout the period of investigation, irrigation wells were measured for water level and sampled for water quality. Total well depth, aquifer penetration, and potentiometric level were analyzed to determine their relationship to chloride concentration by regression analysis and polynomial expansion. The most significant linear relationship was that of chloride concentration and potentiometric level. Data showed that as potentiometric levels decreased as a result of irrigation pumpage, chloride concentration of the irrigation water increased and vice versa. Chloride data for the various sample months were fit to gamma distribution by the method of maximum likelihood to allow water quality estimates to be made for all the wells in the study area based on data from the sampled wells in the study area. Analysis of the gamma distribution indicates that 50 percent of the wells in the study area will produce water with chloride concentration less than or equal to 210 parts per million, and that 10 percent of the wells will exceed 778 parts per million chloride during any time of the year.

A water use inventory of the intensive agricultural area was conducted, and irrigation pumps were rated according to discharge and electrical consumption capabilities. Monthly records of electrical consumption were used to determine amounts of ground water withdrawals which, in the three counties, totaled some 18.5 million gallons per day. The values derived by the electrical consumption method were compared to the water use figures generated by the local agricultural agencies and the U. S. Geological Survey (USGS). In comparison, the county and USGS values were approximately 50 percent higher than those values calculated in this study. To provide a check on the withdrawal figures calculated from electrical consumption, a flow-net analysis was done from the potentiometric map of the study area at the time in which the extent of the cones of depressions were the greatest. Values generated by the flow-net analysis closely agreed with the water use values derived by the electrical consumption method.

INTRODUCTION

The Tri-County area of St. Johns, Putnam, and Flagler counties in northeastern Florida (Figure 1) is the largest producer of cabbage and potatoes in the southeastern United States. Over the years as vegetable production increased, the lands near Orange Mills, Hastings, Elkton, and Bunnell became intensively cultivated (Figure 2). Due to the limited moisture holding capacities of most Florida soils and to an uneven distribution of rainfall events, irrigation of crops is required. In these counties, the Floridan aquifer which underlies this entire area offers large quantities of ground water to the user.

At one time, artesian pressure was great enough that irrigation wells would flow naturally. However, by the early 1950's, artesian water levels had dropped; and free flowing wells could no longer provide enough water for irrigation. Electrically driven pumps were subsequently installed on the wells, and large quantities of ground water were withdrawn in relatively short periods of time resulting not only in the development of cones of depression, but also the production of highly saline water. This contamination of upper fresh water layers of the Floridan aquifer from the lower connate saline water-bearing strata has progressively spread to the point where proper water management is necessary to alleviate the problem.

Although this problem had been acknowledged and some recommendations had been offered prior to the implementation of the Water Resources Act of 1972, a responsible agency with the statutory authority to impose mandatory permitting and regulatory programs did not exist. With the passage of the Water Resources Act of 1972, the St. Johns River Water Management District was established providing a potential vehicle for effective permitting and regulation of the water resources.

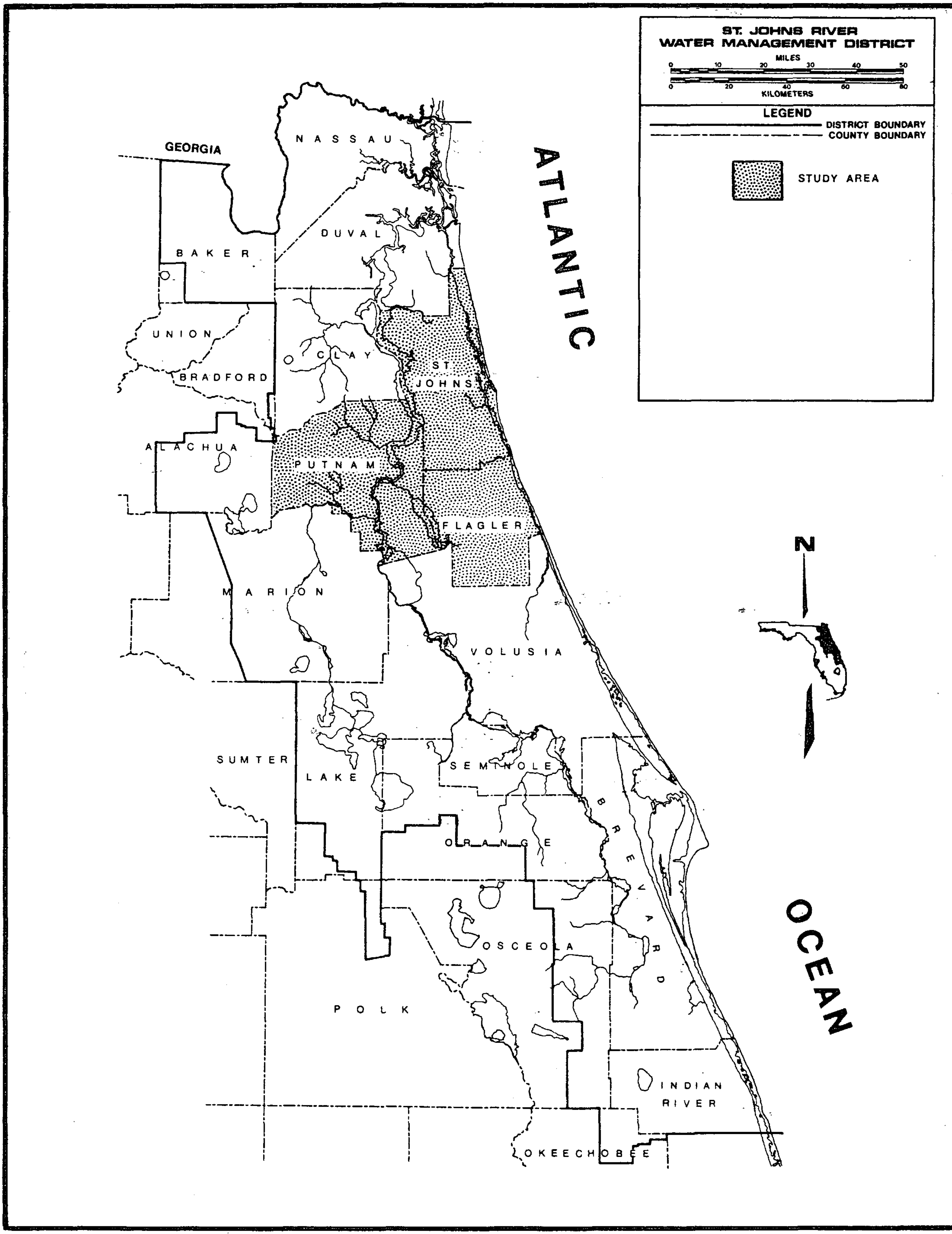


FIGURE 1. -- Delineation of the Study Area

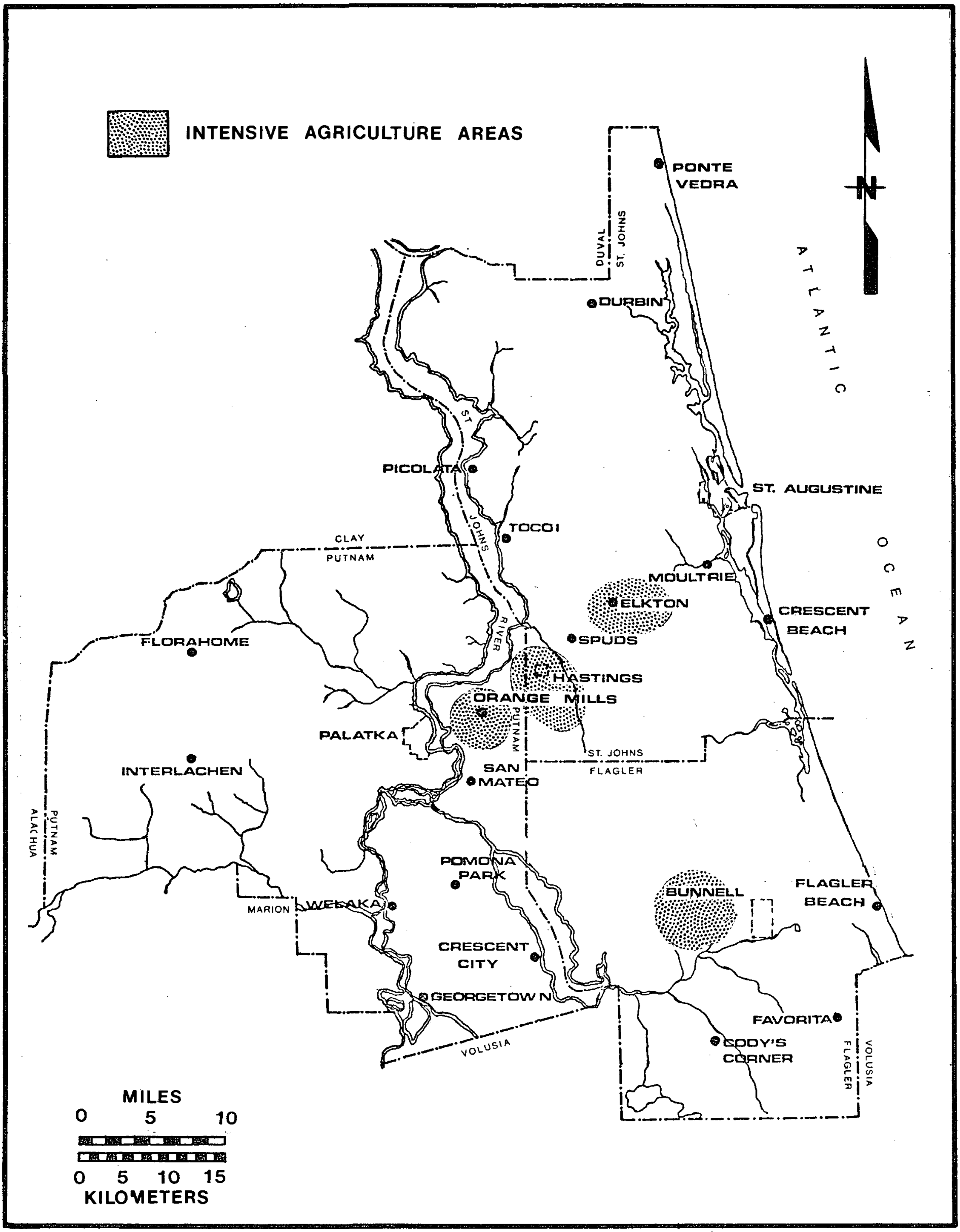


FIGURE 2. -- Location of the Areas of Intensive Agriculture Within Putnam, Flagler, and St. Johns Counties

PURPOSE AND SCOPE

The St. Johns River Water Management District Governing Board recognized the problem of saline water intrusion in the Tri-County agricultural area and considered it an issue worthy of intensive study and thereby authorized this investigation. The goals of the project were to understand the causes of saline contamination and to delineate those areas where it occurs. The data collected would then provide information needed by the District to establish the necessary criteria for technical assistance. By continuing water resource oriented programs in the local agricultural communities, it would be possible to promote new management techniques and conservation practices aimed at protecting the resource for future generations.

The objectives of the study focus on the interrelationships of water quality (chloride concentration), potentiometric levels, hydrogeology, well characteristics and ground water withdrawals in those areas affected by the saline contamination. The data collected by this study will create the foundation for a hydrological data base which can be utilized in future computer modeling and permitting activities in this area.

ACKNOWLEDGEMENTS

The writers wish to express their gratitude to Mr. G. Warren Leve and Mr. Craig Bentley of the U. S. Geological Survey, Northeast Florida Field Office.

Acknowledgements are due to the Bureau of Water Resources of the Department of Natural Resources (DNR) for their initial assistance in geophysical logging, and for their 1970-71 well inventory data of the agricultural areas in Putnam and St. Johns counties.

Thanks are due to the Agricultural Stabilization and Conservation Service (ASCS), the Soil Conservation Service (SCS), and the St. Johns and Putnam County Agricultural Extension agents for their continued cooperation throughout the study.

Special appreciation is offered to the vegetable growers of St. Johns, Putnam, and Flagler counties whose cooperation was necessary for the completion of the study.

Thanks are extended to Ms. Jill Medrum of the Hastings IFAS Experimental Station who kindly assisted us in obtaining and processing rainfall data in the Tri-County agricultural area.

Cooperation by Daytona and Palatka offices of the Florida Power and Light Company in obtaining electrical consumption data is sincerely appreciated.

Thanks to ITT Palm Coast and Leggette, Brashears, and Graham who released hydrogeologic data for our utilization.

The authors wish to express a special thanks to Dr. D. V. Rao for his technical assistance in all statistical analysis in this report.

PREVIOUS INVESTIGATIONS

A study of the geology and ground water resources of St. Johns, Putnam, and Flagler counties was conducted by the U. S. Geological Survey in cooperation with the Florida Geological Survey. The results of that study are presented in Report of Investigation No. 32 and Information Circular No. 37, both by Bermes, Leve, and Tarver, 1963. Although some of the problems that are covered by this report were brought to light by the 1963 publications, no water management programs existed at that time, and the situation worsened.

In 1970 the Department of Natural Resources, Bureau of Water Resources, inventoried more than 1,200 irrigation wells in Putnam and St. Johns counties. The reasons for the inventory were to determine chloride concentration and to locate and list abandoned and wild flowing wells. Again, no remedial programs were enacted after completion of the inventory. In an effort to utilize the data that was collected, the Bureau of Water Resources in 1975 employed its geophysical logger to further study the geology of the area. Although the product was an unpublished report (Plappert, Johnson, Helpling, 1975), copies were made available to the U. S. Geological Survey and the St. Johns River Water Management District for their utilization.

RESEARCH METHODOLOGY

The initial phase of the study involved an office review of the 1963 U. S. Geological Survey data and the 1970 Department of Natural Resources data. Common data points (observation wells) were determined, followed by field reconnaissance and incorporation of available wells into an observation and sampling network. From the resulting network, extensive sampling was conducted during periods of maximum and minimum water levels in the Floridan aquifer. A smaller network was incorporated into the study to monitor monthly fluctuations and establish any existing chloride and water level relationships. The sampling program was initiated in March 1975 and completed for this study in September 1976. Additional information was collected during the inventory which included well depth, density, and location. These tabulated data may be found in Technical Memorandum No. 2, Supplemental Data for Report of "Saline Contamination of a Limestone Aquifer by Connate Intrusion in Agricultural Areas of St. Johns, Putnam, and Flagler Counties, Northeast Florida", St. Johns River Water Management District, Palatka, Florida, July 1979.

To construct isochlor and potentiometric maps for the Tri-County study, it was necessary to utilize a large number of wells in order to obtain adequate detail. Unfortunately, due to the type of well construction and to the large seasonal variation in potentiometric levels as a result of pumping, it was not feasible to obtain both chloride and potentiometric levels of all common wells during each sampling run. Both chloride concentrations and water levels were obtained during free flowing conditions; however, during pumping conditions, only a water sample could be acquired. During non-flowing conditions, it was sometimes possible to prime the pumps of individual wells to collect samples; but often this was impossible due to water levels too far below land surface for the pump to operate or because the electrical power had been turned off.

Water withdrawal was calculated in order to derive a relationship between ground water withdrawals and salt water contamination. The manner in which ground water withdrawals were determined involved obtaining electrical consumption values from Florida Power and Light Company and field rating of selected pumps in the Tri-County area for discharge and electrical consumption. Linear regression analyses were performed to obtain electrical consumption and water withdrawal relationships within individual cones of depression. Monthly and average annual pumpage values were derived for individual cones of depression.

Eighty-two Floridan wells in the Tri-County agricultural area were geophysically logged in order to delineate the top of the Ocala Group, the thickness of the overlying Hawthorn Formation (if present), and the top of the Avon Park Formation. In particular, double electrode resistivity and spontaneous potential curves, gamma ray profiles and caliper logs were utilized to delineate the above-mentioned formations and formational contacts. Current meter profiles, temperature profiles, and downhole water samples were useful in defining flow zones and associated water quality.

As a part of the U. S. Geological Survey/St. Johns River Water Management District Cooperative Agreement, the U. S. Geological Survey conducted pumping tests and recovery tests to define aquifer characteristics in the study area (Bentley, 1977). This information was used to supplement the previous investigations in areas where data were not available.

GEOGRAPHY

CLIMATE

The climate in the Tri-County area is classified as humid subtropical. The mean annual temperature is about 70°F near the coast and 72°F for the inland area. The mean monthly temperatures range from approximately 58°F in December to 81°F in August. During the fall and winter months, it is not uncommon that the area experiences freezing temperatures associated with cold fronts.

Rainfall in the area occurs as two general types. Summer rainfall events occur as local showers and thunderstorms, resulting from convectional activity. Rainfall during the winter months is widespread and generally associated with frontal activity. During the period from 1955 through 1975, the mean annual rainfall at the Palatka NOAA Station was 53.23 inches. Figure 3 illustrates the 30-year mean annual rainfall isohyetals for the period of 1941 through 1970. Normally, over 50 percent of the annual rainfall occurs during the four month period of June through September. The driest months during an average year are from late October through May, with November being the month of lowest rainfall. This dry period coincides with the growing season (Figure 4) of vegetables in the Tri-County area which makes irrigation by ground water a necessity.

PHYSIOGRAPHY

Topography of the Tri-County area is generally flat with very gently sloped streams which drain to low-lying areas. Most of the area is located within the Eastern Valley subdivision (Figure 5) of Florida (White, 1970) which is a broad, flat, coast-parallel valley. It is bounded to the east by the Atlantic Coastal Ridge. The western boundary is the Palatka Hill and Crescent City Ridge, both

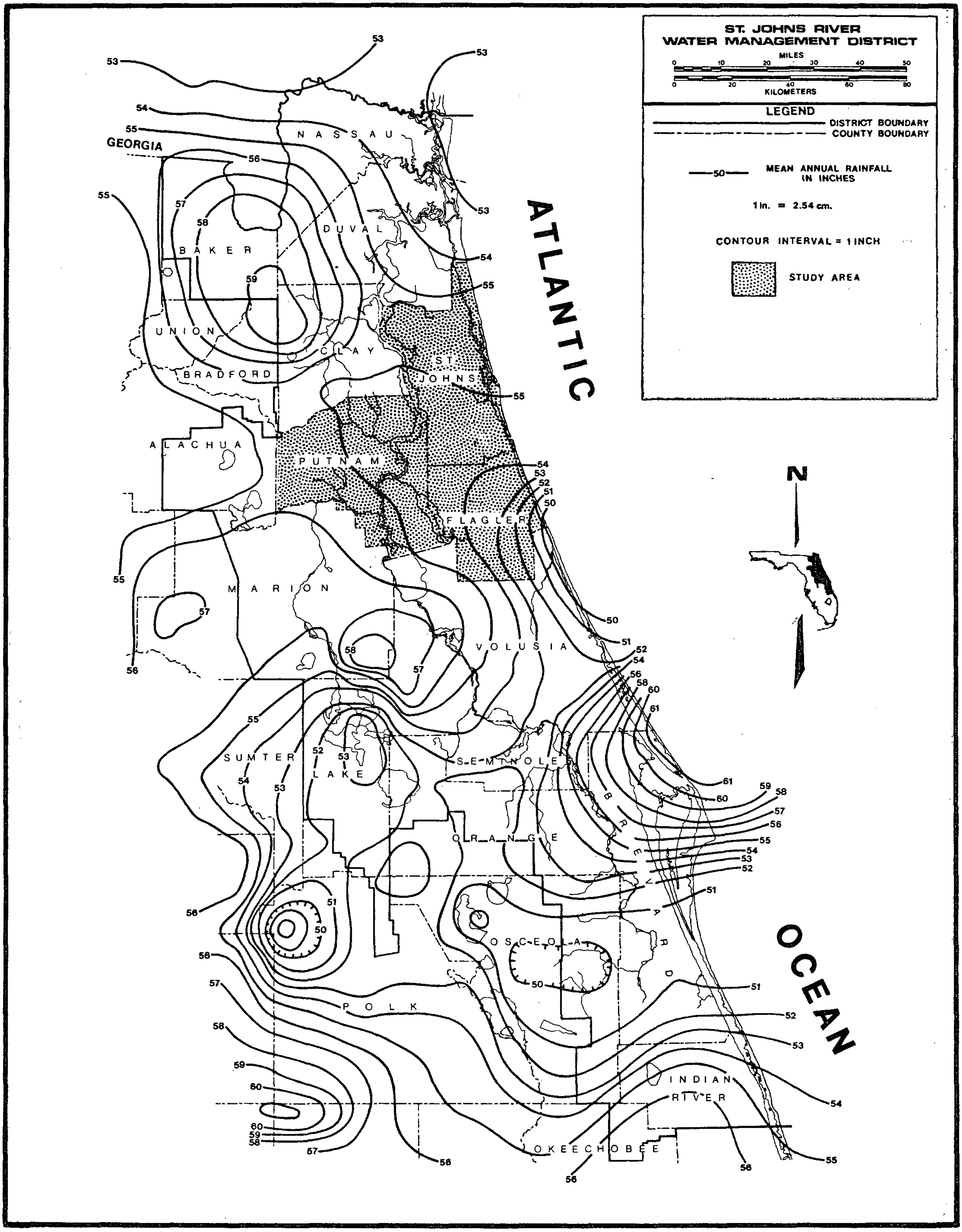


FIGURE 3. -- Mean Annual Rainfall for the Period of Record 1941-1970

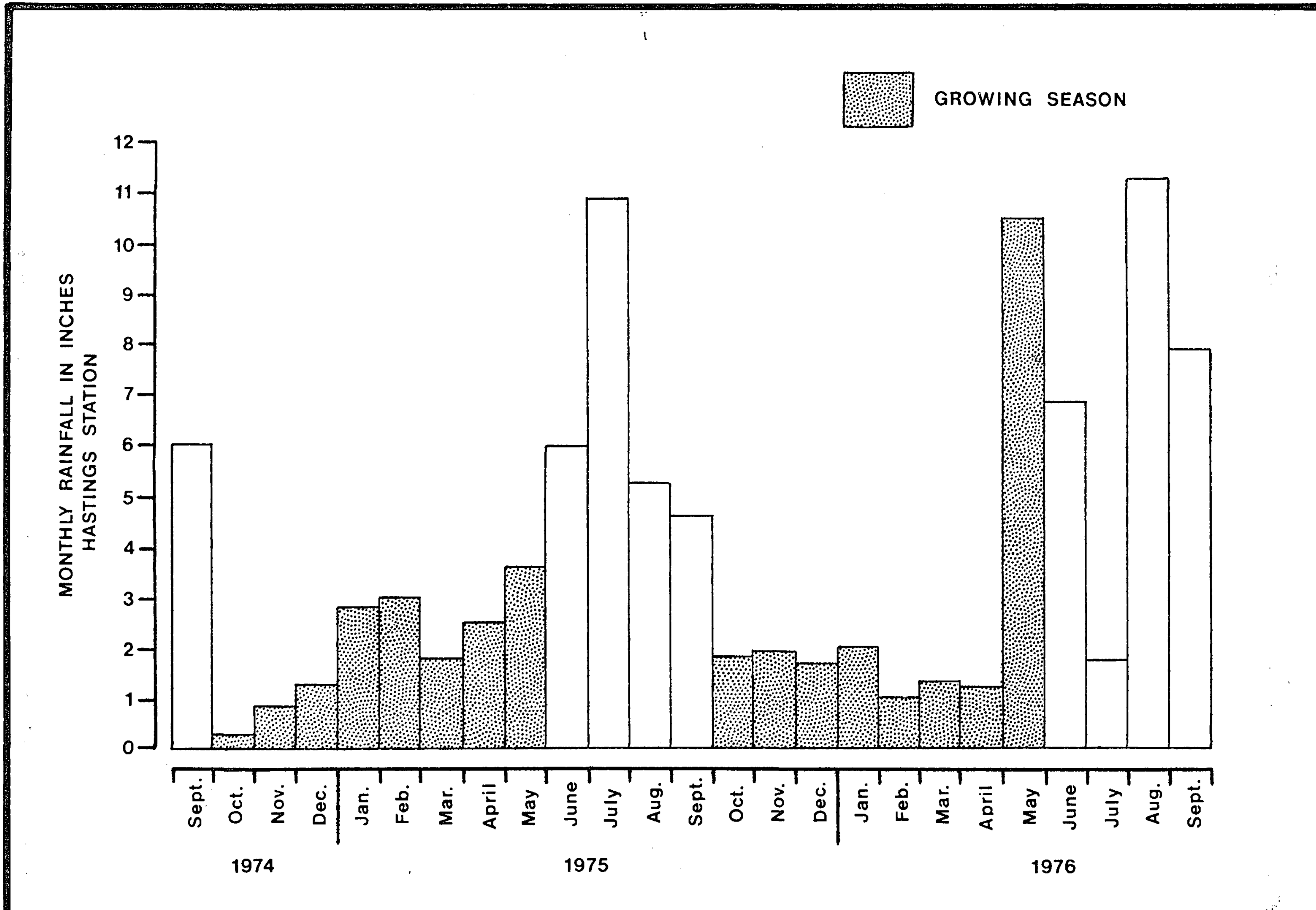


FIGURE 4. -- Monthly Rainfall Totals from September 1974-1976 and the Associated Months of the Growing Season

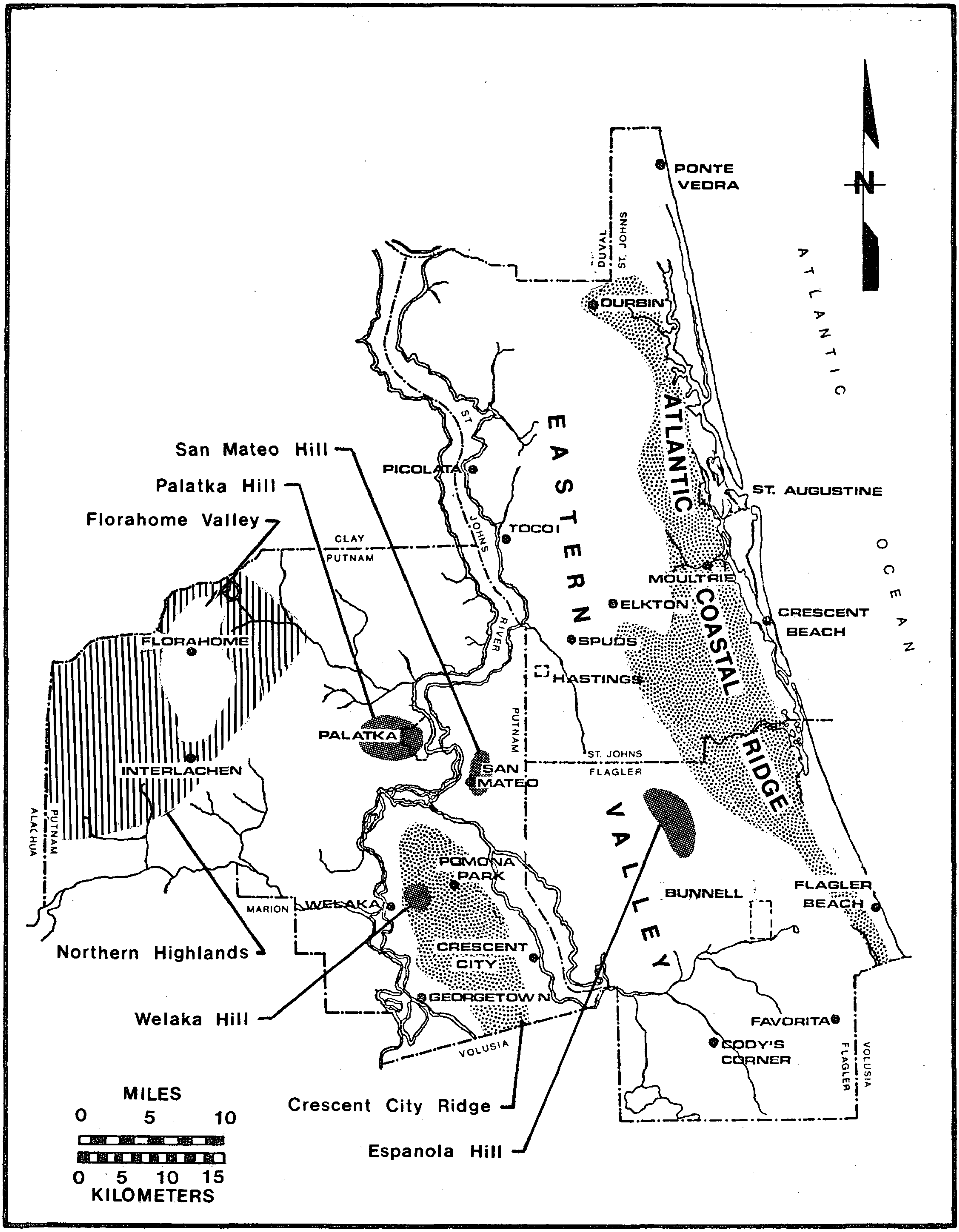


FIGURE 5. -- Physiographic Features of the Tri-County Study Area

of which are probably remnants of a once continuous ridge system. Elevations range from a few feet above mean sea level (msl), where the St. Johns River occupies the valley floor to approximately 45 feet msl. Two smaller hills are prominent--the Espanola and San Mateo Hills. The Espanola Hill, located in north central Flagler County in close proximity to the Atlantic Coastal Ridge, is elongate in a north-northwest to south-southeast direction. The San Mateo Hill, located just south of East Palatka on the east side of the St. Johns River, is rather small in size compared to the aforementioned physiographic features.

Cooke (1939) recognized several marine terraces. These terraces are generally flat areas cut by the action of marine erosion during higher stands of sea level. Generally, in the Tri-County project area, two terraces can be recognized--the Talbot Terrace at 42 feet above msl elevation and the Pamlico Terrace at 25 feet above msl elevation, both of which have been dissected by erosion.

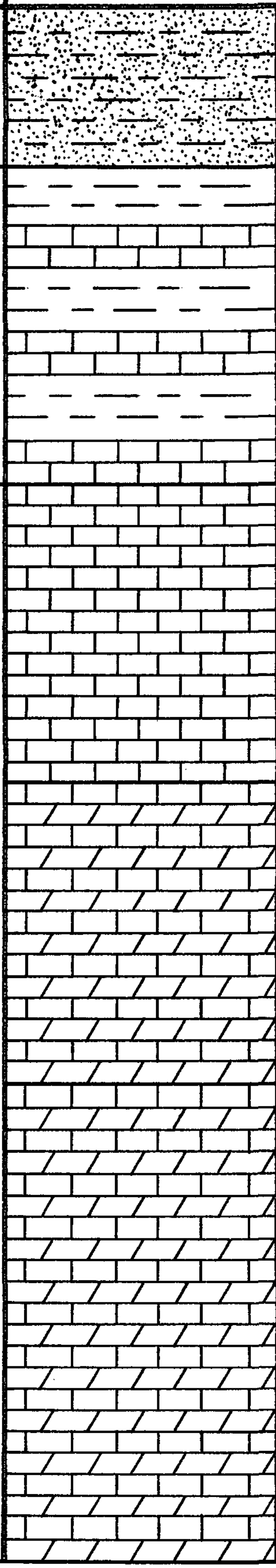
GEOLOGY

Rock units considered in this report in ascending order include the Lake City Limestone, the Avon Park Limestone, the Ocala Group (Crystal River limestone and Inglis limestone), the Hawthorn Formation, and a generally clastic surficial unit. Published descriptions (Chen, 1965; Clark et al., 1964; and Bermes et al., 1963) of each unit are compared with data obtained from geophysical logs to develop the descriptions in the following paragraphs. Figure 6 shows a geologic column for the Tri-County area.

The Lake City Limestone of Middle Eocene age consists of limestone beds, alternating with thick beds of hard dolomite and disseminated peat as well as peat occurring as distinct beds. Peat occurs throughout the formation as scattered flecks; and at the top of the formation, there are typically one or more distinct beds of peat with more peat and peaty carbonate beds occurring throughout. These beds typically wash out or collapse as wells are pumped which is depicted on geophysical logs as a large cavity. The top of the formation is taken to be the highest correlatable peat bed in the section.

The Avon Park Limestone of Middle Eocene age consists of alternating beds of dolomite and limestone with some disseminated peat. In some cases of the study, a peat bed occurs near the middle of the formation. The uppermost bed of hard dolomite is taken as the top of the formation. This horizon is the "Avon Park low porosity zone" (Johnson, 1979). The Avon Park Limestone is characterized by showing a higher average resistivity than the Ocala Group. Figure 7 is a map showing the elevation of the top of this formation in the study area.

The Ocala Group of Late Eocene age consists of generally soft pure limestone. Slightly harder, more consolidated limestone beds occur near the bottom of the group. Differentiation of the Ocala into two formations, the Crystal



AGE	FORMATION	THICKNESS	DESCRIPTION
RECENT TO MIOCENE	CLASTICS	0 to 100 ft 0 to 30m	Sand, Clay, and Mixtures of the Two
MIOCENE	HAWTHORN FORMATION	3 to 180 ft 1 to 55 m	Clay, with Sand, Sandy Clay and Sandy Limestone
EOCENE	OCALA GROUP	90 to 250 ft 30 to 75 m	Soft, Pure Limestone
EOCENE	AVON PARK LIMESTONE	150 to 250 ft 45 to 75 m	Alternating Limestone and Dolomite Beds with some Disseminated Peat and some Thin Peat Beds
EOCENE	LAKE CITY LIMESTONE	400 to 500 ft 120 to 150 m	Alternating Limestone and Dolomite Beds with Disseminated Peat and Distinct Peat Beds

FIGURE 6. -- Geologic Column Showing Formations in the Tri-County Study Area

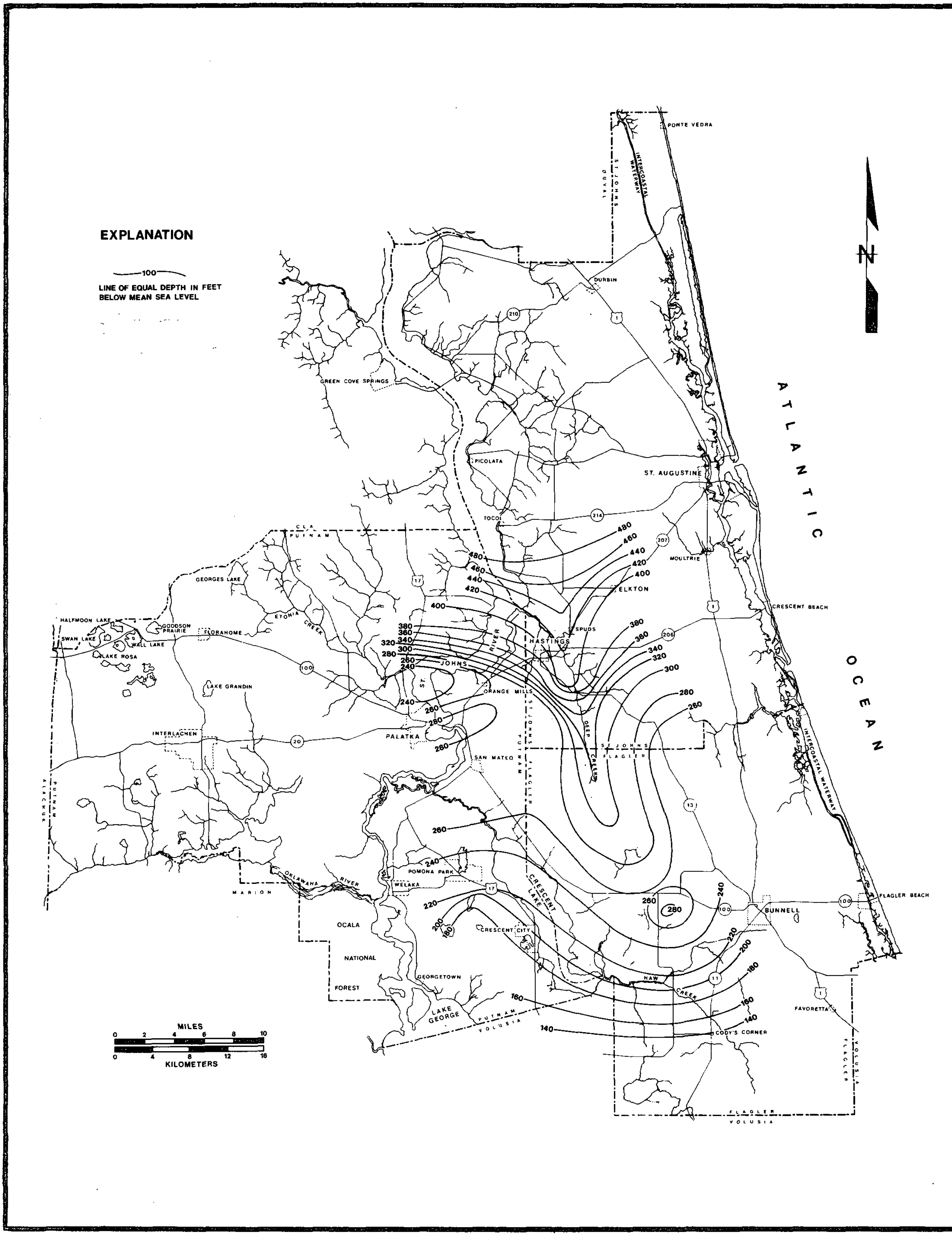


FIGURE 7. -- Elevation of the Top of the Avon Park Limestone

River limestone (upper) and the Inglis limestone (lower) is accomplished by means of the natural gamma ray log which shows the Crystal River as generally pure limestone and the Inglis slightly less pure (higher gamma ray intensity). Figure 8 shows the line (A-A') that approximates the southernmost appearance of the Crystal River limestone. The Inglis limestone as used in this report includes both the Williston limestone and Inglis limestone of Puri (1957). Figure 8 is a map showing the elevation of the top of the Ocala Group in the Tri-County area.

The Hawthorn Formation, Middle Miocene to possibly Late Miocene in age, consists of clastic material, mainly clay and sandy clay, interbedded with hard dolomite or limestone beds. Both clay and limestone contain phosphatic material. Beds of very hard dolomite or dolomitic limestone occur throughout the formation, and an especially hard, usually non-porous, sandy dolomitic limestone bed forms the base of the formation. Figure 9 is a map showing the elevation of the top of the Hawthorn Formation. Figure 10 shows depth to the basal limestone bed of the Hawthorn Formation, commonly called "Top of Rock". This bed typically contains a rather high concentration of phosphatic material and is generally about 5 to 15 feet in thickness. The top of the formation is picked at the top of the phosphate containing bed nearest the surface. The contact between the Hawthorn Formation and the Ocala Group is very pronounced in geophysical logs. The quite pure limestone of the Ocala Group contains no phosphatic material, whereas the lowest Hawthorn carbonate bed characteristically has the greatest phosphate concentration.

The clastics, Late Miocene to Recent age, consist of non-phosphatic sand and clay with relatively thin beds of limestone occurring in some areas. Since this unit is typically cased off, gamma ray logs are the only available means of study in wells. Clean non-clayey sand occurs at and very near land surface. Sandy clay and clayey sand occur below the clean sand.

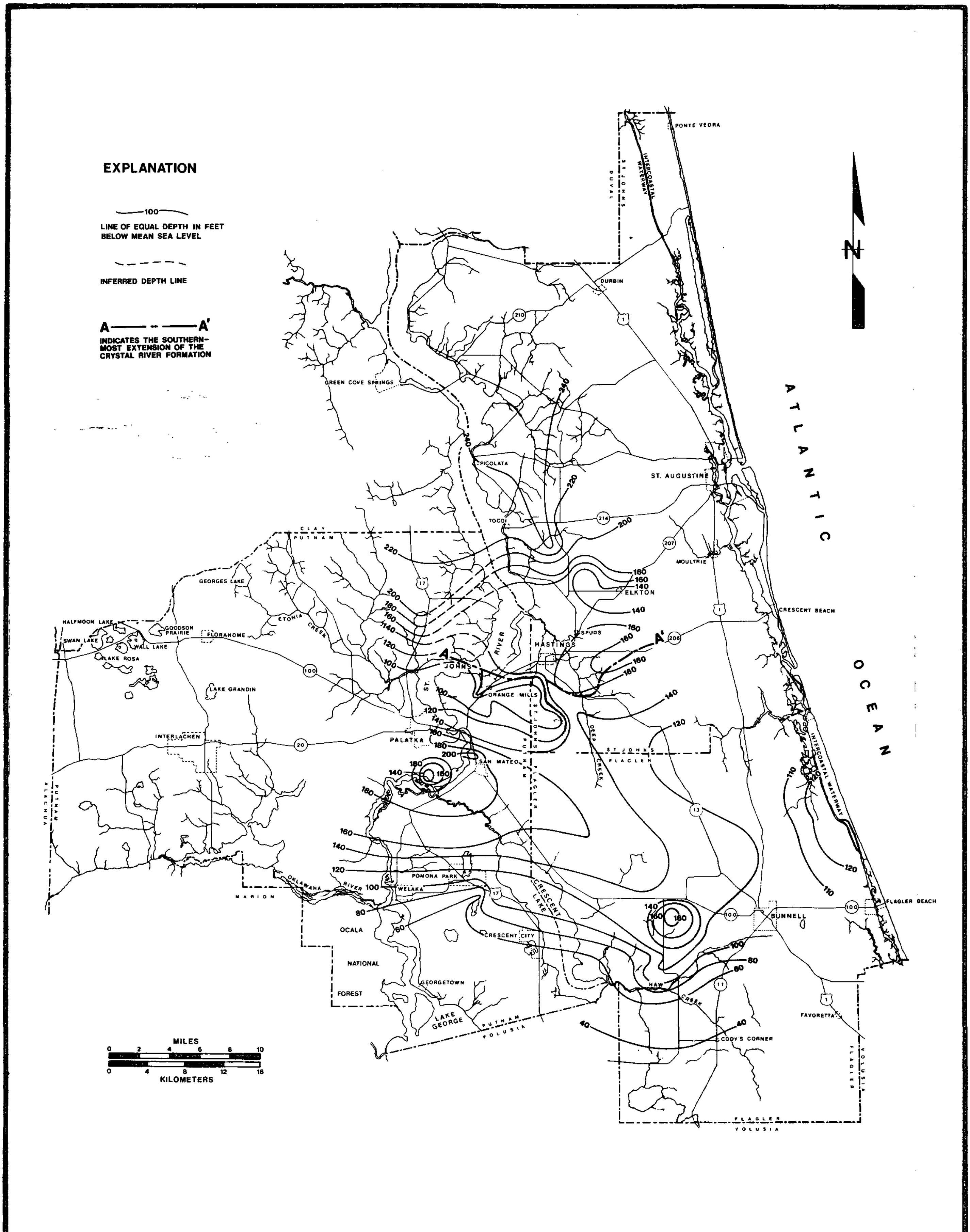


FIGURE 8. -- Elevation of the Top of the Ocala Group Limestone

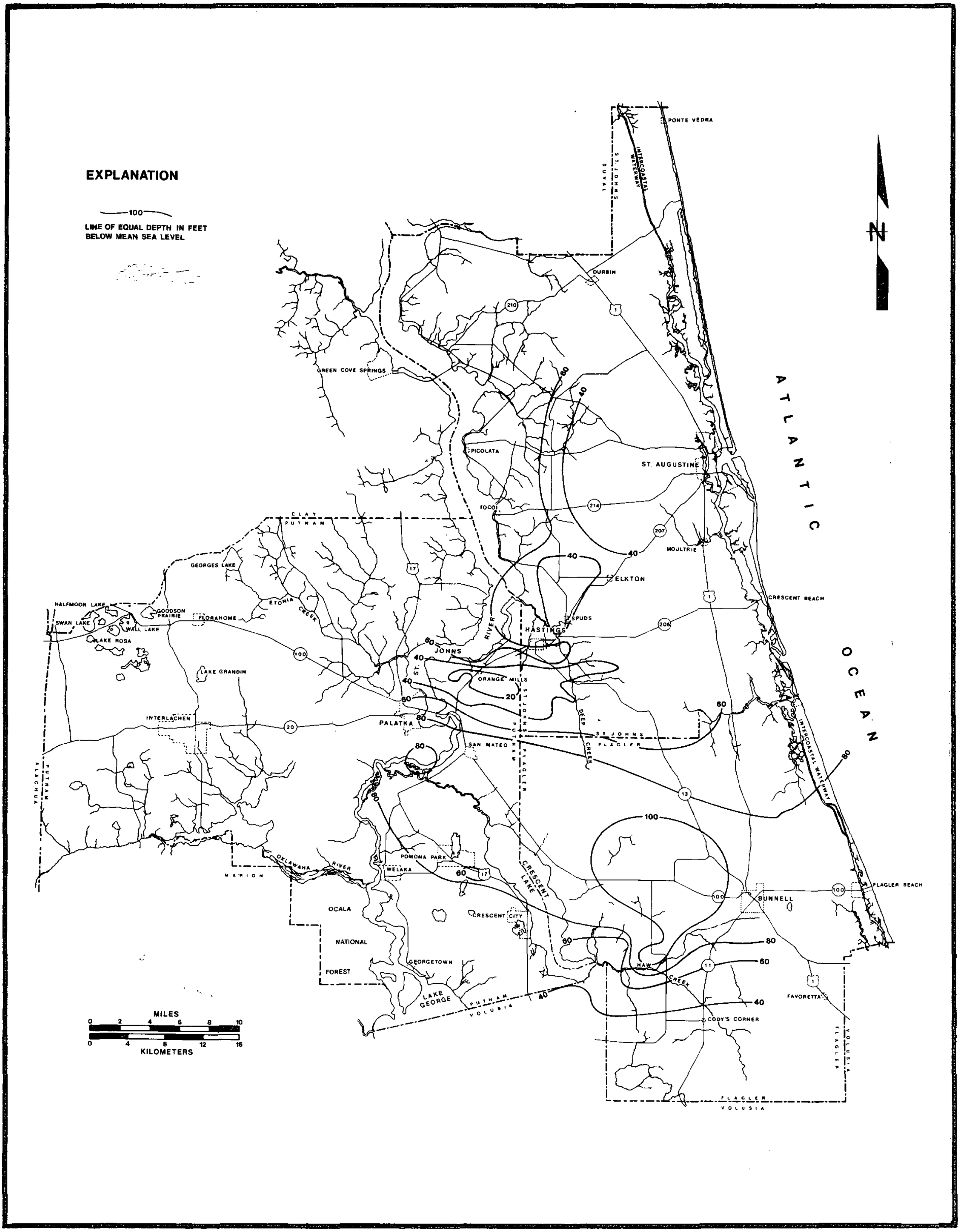


FIGURE 9. -- Elevation of the Top of the Hawthorn Formation

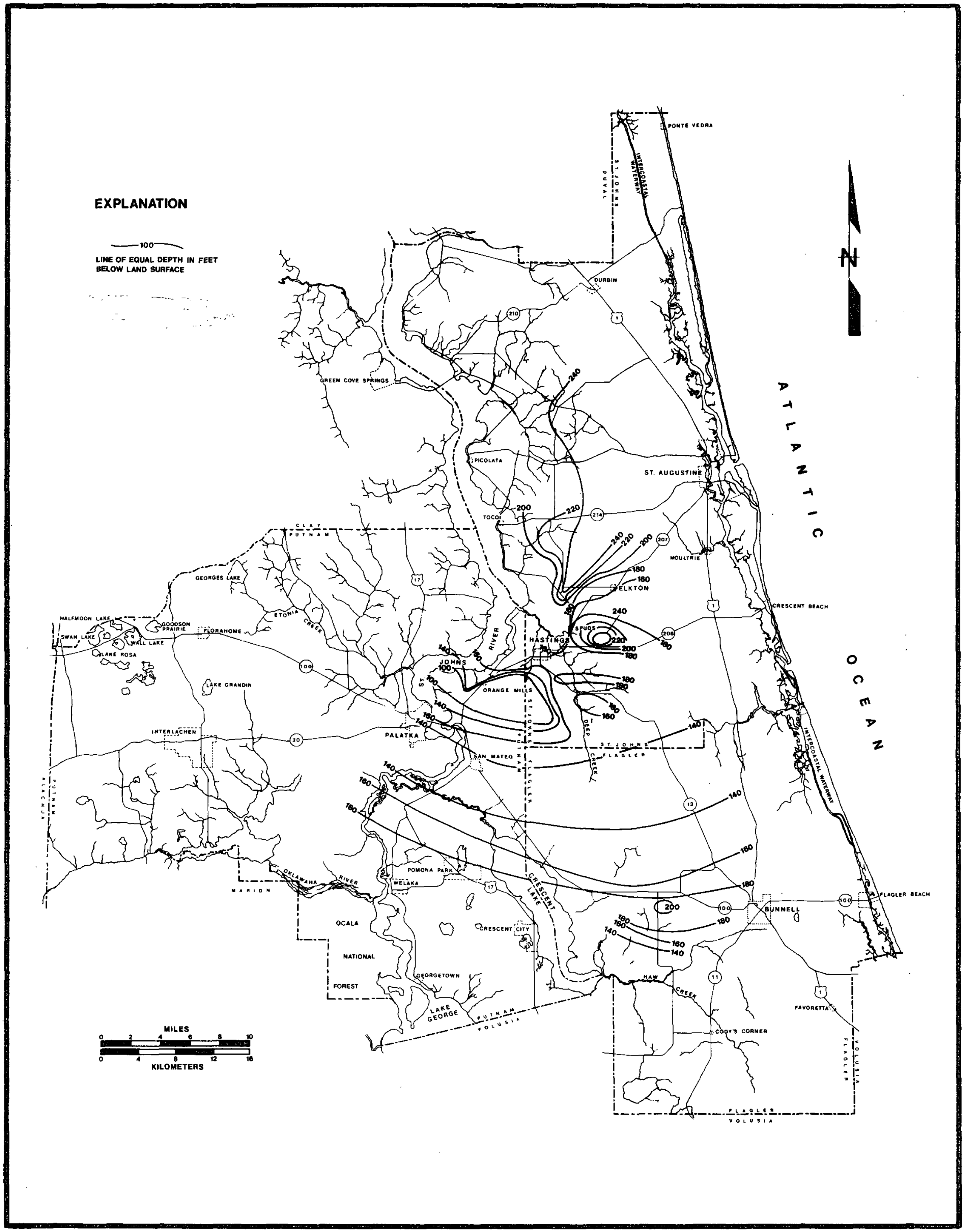


FIGURE 10. -- Depth Below Land Surface of the Top of the Basal Limestone Unit of the Hawthorn Formation

GEOPHYSICAL LOGGING

For this study, 82 wells were geophysically logged to obtain geologic and hydrologic information (Figure 11). The wells ranged from 113 feet Total Depth Logged (TDL) to 1,656 feet TDL. Four were test and/or observation wells, 38 were active irrigation wells, and 40 were presently unused or abandoned irrigation wells. Complete tabular data concerning all wells geophysically logged may be found in Technical Memorandum No. 2, Supplemental Data for Report of "Saline Contamination of a Limestone Aquifer by Connate Intrusion in Agricultural Areas of St. Johns, Putnam, and Flagler Counties, Northeast Florida", St. Johns River Water Management District, July 1979.

Generally, four types of geophysical logs were run. Logs were run in the following order: (1) caliper log: continuously records borehole diameter and is used to correct electric log quantitative values; (2) electric log: records the electrical resistivity of the lithological material in the open hole (uncased) from which correlations can be made; (3) natural gamma ray log: measures the natural gamma ray radiation intensity within the well (both cased and uncased) from which lithology can be deduced; and (4) flow meter logs run when the well is flowing naturally or is being pumped and shows water producing zones.

Downhole water samples were also taken. Samples were taken only after the well had been undisturbed for at least one day and collected from top to bottom of the well to insure minimum disturbance and mixing.

FLOW METER AND DOWNHOLE SAMPLES

Flow meter logs were run on 30 of the 82 geophysically logged wells in the study area to determine water production zones. Wells were either flowing naturally or were pumped by a portable centrifugal pump to obtain the necessary

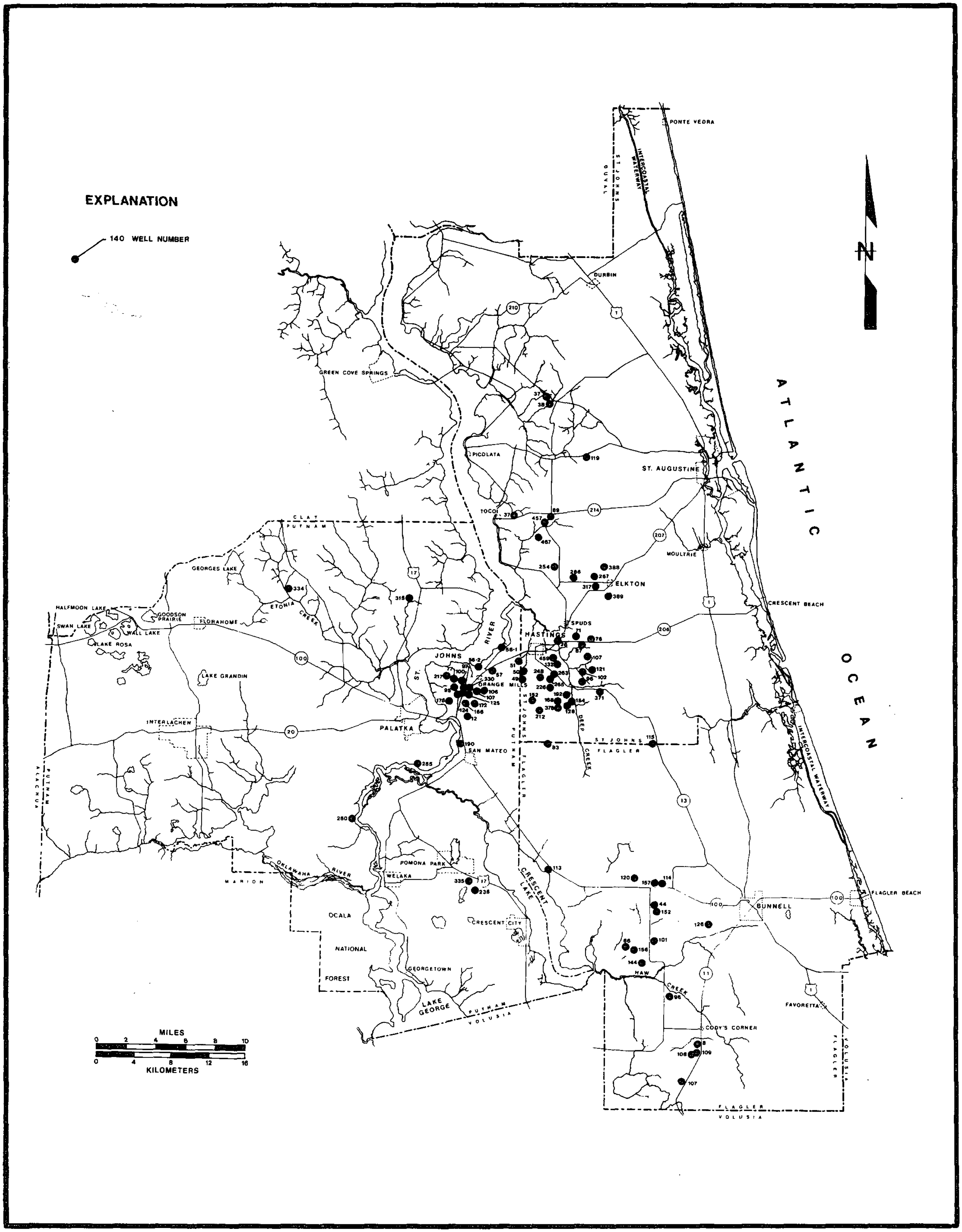


FIGURE 11. -- Location of Wells Geophysically Logged in the Tri-County Study Area (Note: Geophysical Data for Each Well May be Found in SJRWMD Technical Memorandum No. 2)

flow. Generally, the shallower wells penetrate only the Ocala Group limestone and obtain water from a single distinct zone. In deeper wells and in several Ocala wells, two or more zones of production are characteristic. Correlation between producing zones was attempted on the basis of depth below land surface and on the basis of relative position within each formation. However, there was no correlation between most zones even when the wells were closely spaced. Only one producing zone was established by correlating relative position within the Ocala Group. Twenty of the 30 flow meter logged wells obtained some water from the upper 50 feet of the Ocala Group limestones which is close to the Ocala Group/Hawthorn Formation contact. Nine of the 30 wells derived at least some water at the contact. Typically, the upper 50 feet of the Ocala Group exhibits secondary porosity in the form of solution cavities which are depicted on caliper logs as irregularities in the borehole wall.

A water sample was taken from the bottom of 42 of the 82 logged wells; and in addition, 13 of those wells (Avon Park limestone or deeper) were sampled at selected depths within the borehole. All continuous deep sampling was done under non-flowing conditions. In these selected wells, a water sample was obtained from just below the bottom of the casing. Remaining samples were obtained from successively deeper flow zones in each well in order to reduce mixing. In deep wells outside the study areas, chloride concentration is low throughout the entire borehole. Deep wells just within the areas of maximum contamination show generally increasing conductivity toward the bottom of the hole or as the deepest water-producing zone is approached. In the centers of the contaminated areas, conductivity is relatively high throughout the entire borehole. In some of these contaminated wells, the producing zone at the Hawthorn/Ocala contact shows relatively low conductivity values when compared to samples obtained from deeper in the well or samples taken above the contact.

HYDROGEOLOGIC REGIME

RECHARGE-DISCHARGE AREAS

The principal recharge area for the agricultural areas of Putnam and St. Johns counties is located in the sandhill and lakes region of western Putnam and Clay counties and is sometimes referred to as the "Northeast Florida Potentiometric High". Flow-net analysis (Phelps, 1978) substantiates active recharge occurring within the "Northeast Florida Potentiometric High" which subsequently flows to the agricultural areas of St. Johns and Putnam counties. During the growing season, major discharge in the agricultural areas is in the form of pumpage; recharge, at this time, is supplied by leakage from over and underlying formations. Unfortunately, the quantities of leakage derived from those sources is not sufficient to stabilize the enlarging cones of depression. During the non-growing season, the potentiometric surface recovers significantly to produce free-flowing wells and artesian springs (Figure 12).

Although the "Northeast Florida Potentiometric High" undoubtedly contributes some recharge to the agricultural area in Flagler County, the principal recharge for the Bunnell cone occurs in the areas of northcentral Volusia and southern Putnam counties (Figure 13). Discharge from wells occurs during the pumping season which is from September through May. During the non-pumping season of June through August, the potentiometric surface typically remains below land surface, minimizing any loss through free-flowing wells. However, natural discharge occurs throughout the year along Haw Creek and Middle Haw Creek (Bermes, Leve, Tarver, 1963). Additional discharge occurs through springs in Crescent Lake and along the St. Johns River in the vicinity of Welaka and Lake George.

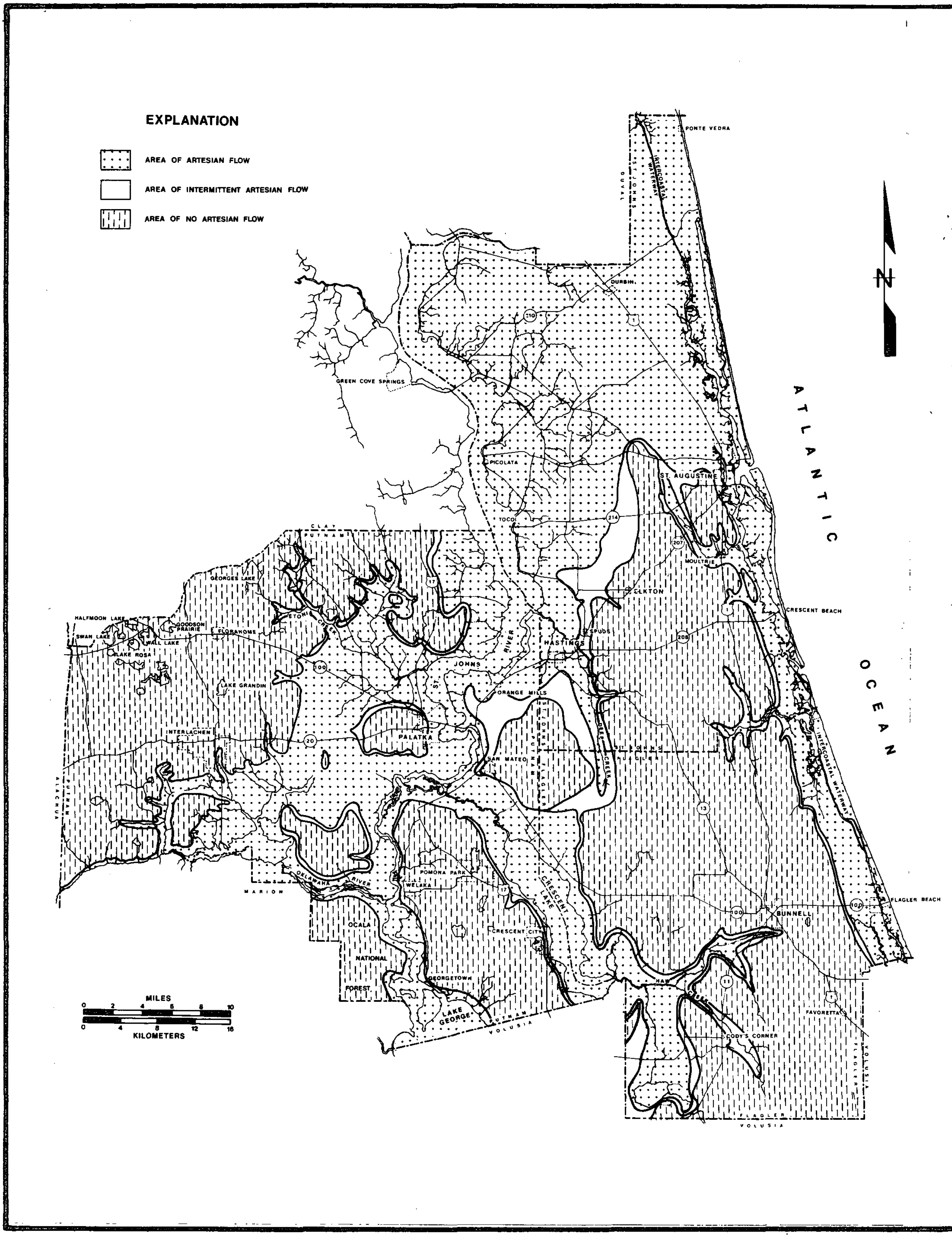


FIGURE 12. -- Areas of Artesian Flow Within the Tri-County Study Area

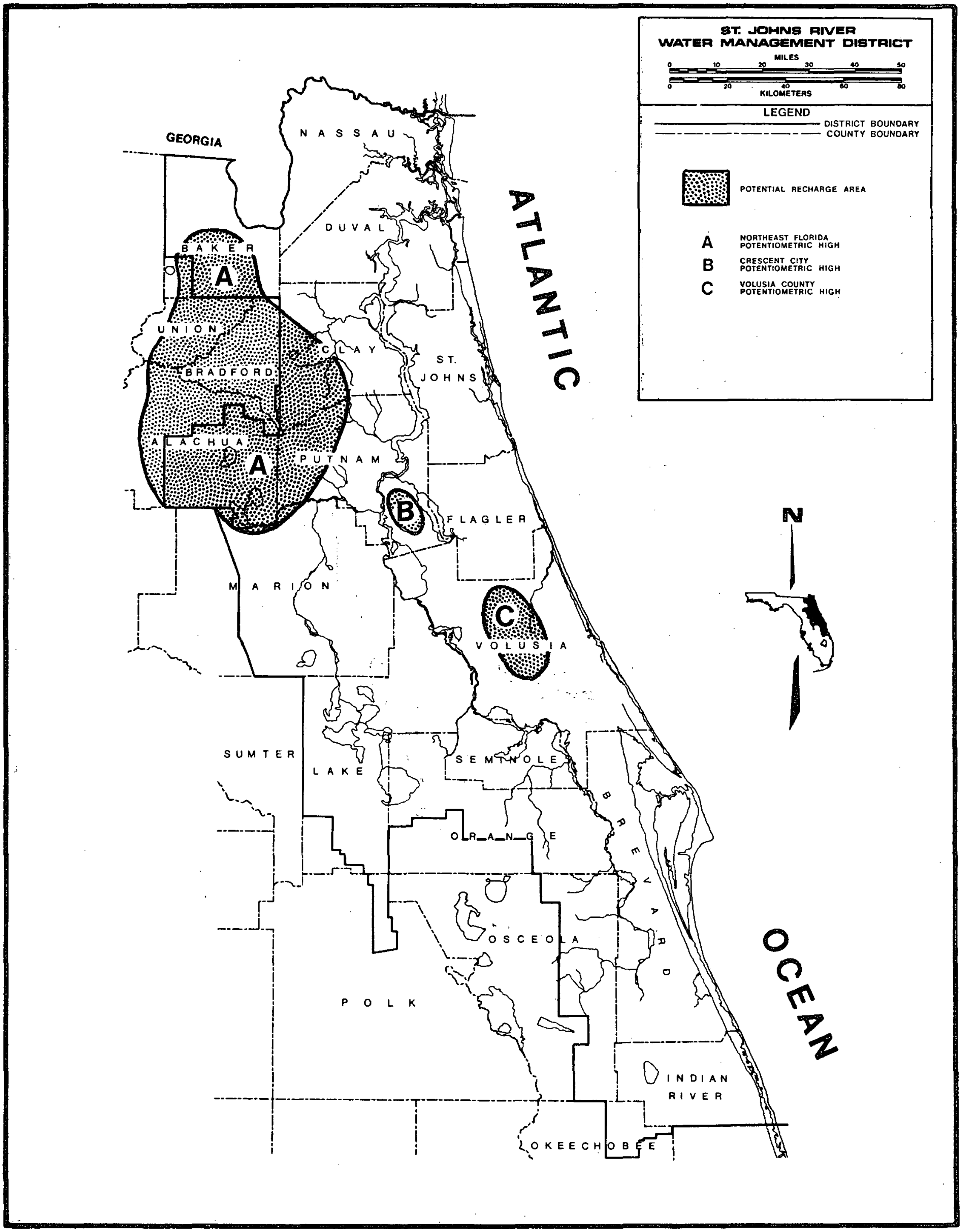


FIGURE 13. -- Generalized Map of Potential Recharge Areas in the Vicinity of the Tri-County Area

SEASONAL FLUCTUATIONS IN POTENTIOMETRIC LEVELS AND CHLORIDE CONCENTRATIONS

Potentiometric level observations and chloride concentration measurements were made during the months of March 1975, July 1975, September 1975, May 1976, and September 1976 in order to define seasonal fluctuations in the Floridan aquifer. Several methods of data analysis were utilized in order to delineate any significant trends or relationships. Attempts were made to relate chloride concentration to potentiometric level, aquifer penetration and well depth, using regression analyses. The general distribution of chloride concentration in wells in the study area was determined by fitting the data to probability distributions. Trend analysis of mean chloride concentrations, mean potentiometric levels, isochlor maps, and potentiometric level maps were also included in the study. For a more extensive description of the statistics used in the following sections, refer to Technical Memorandum No. 2, Supplemental Data for Report of "Saline Contamination of a Limestone Aquifer by Connate Intrusion in Agricultural Areas of St. Johns, Putnam, and Flagler Counties, Northeast Florida", St. Johns River Water Management District, July 1979.

Description of Data

The data collected for different analyses presented in this section consist of potentiometric level and chloride concentration on the date of observation, depth of the well, and the depth of aquifer penetration of the well. The observation wells were generally distributed throughout the study area (Figure 14). However, observations were not made at all wells during all the study months. Occasionally, depending on field conditions at certain wells, only the potentiometric level or the chloride concentration could be measured. At some wells, if conditions permitted, additional observations were made during months other than

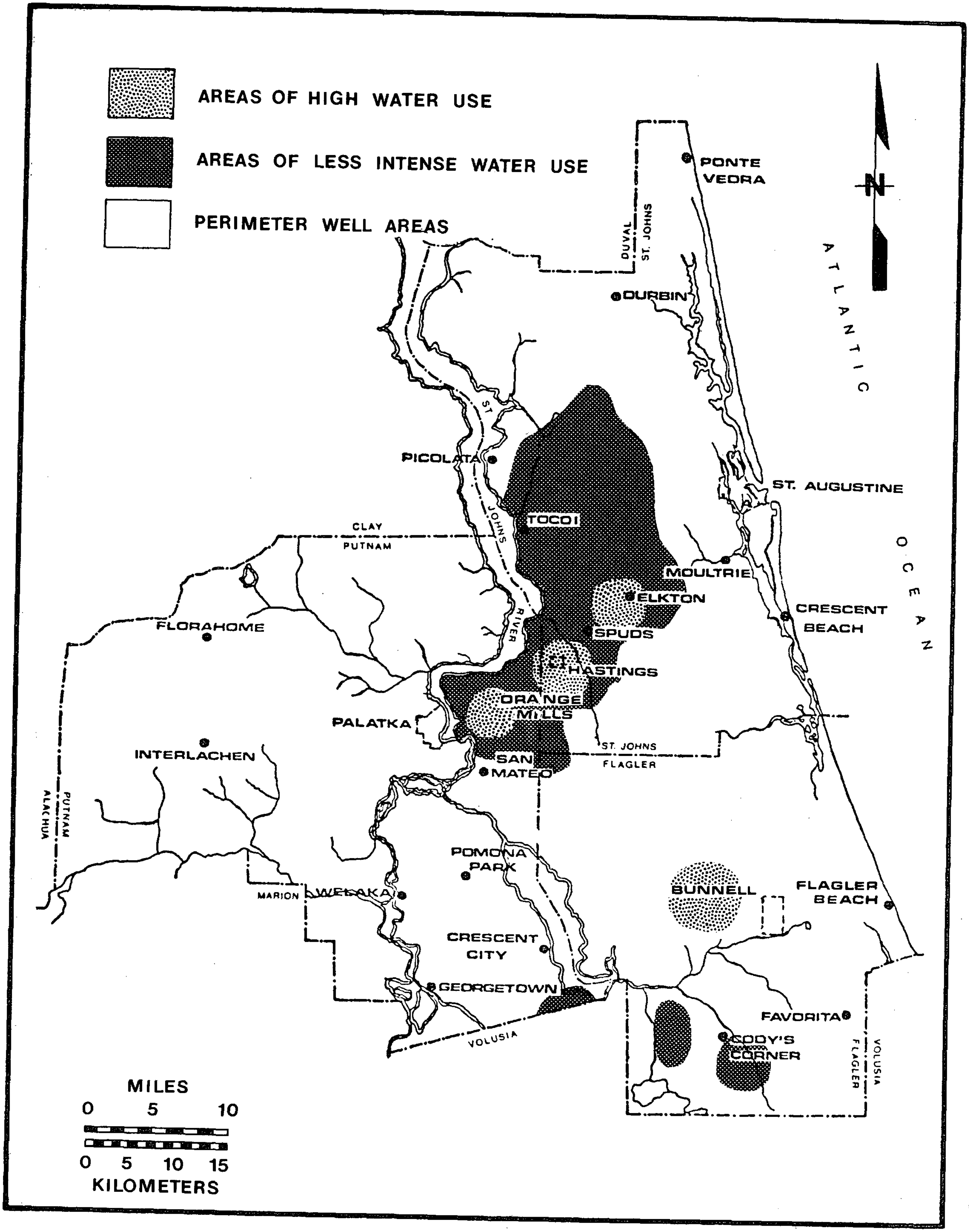


FIGURE 14. -- Generalized Location of Observation Wells Sampled

scheduled sampling months. The density of wells in the specific study areas (Elkton, Hastings, Orange Mills, and Bunnell) is given in Table 1. In the remainder of the study area, the density of observation wells was less. The number of observations for all wells for a given month ranged from 81 to 97 for the months of March 1975, July 1975, September 1975, and May 1976; only 32 observations were made for September 1976. Also, the areal distribution of the observation wells used in September 1976 differed greatly from other months. The data for September 1976 were, therefore, omitted in some statistical analyses.

The range of observed chloride concentrations in the five months varied from lows of 2 to 10 ppm to highs of 3,260 to 3,410 ppm. However, the number of observations with a chloride concentration greater than 1,000 ppm was not more than five in any month.

Regression Analysis

The objective of the regression analysis is to determine the 'best' regression equation for the following cases: (1) for each study month for all wells in the study area, (2) a general relationship (all months) for all wells in the study area, (3) a general relationship (all months) for the wells in each specific study area, and (4) a general regression equation for individual wells.

The dependent or response variable Y (chloride concentration in the present case) may be related linearly to independent variables X_1, X_2, X_3, etc. by the following equation

$$Y = C_o + C_1X_1 + C_2X_2 + C_3X_3 + \dots \quad (1)$$

TABLE 1. -- Well Construction Characteristics and Fluctuations of Potentiometric Levels and Chloride Concentration for all Wells Sampled During March 1975 and September 1975

LOCATION	TOTAL ACRES	MEAN WELL DEPTH (FT.)	WELL DENSITY (WELL/ ACRE)	MARCH 1975 MEAN WATER LEVEL (FT.) (MSL)	SEPT. 1975 MEAN WATER LEVEL (FT.) (MSL)	MEAN CHANGE IN WATER LEVEL MAR-SEPT'75 (FT.)	MEAN MAR'75 CHLORIDE VALUE (PPM)	MEAN SEPT'75 CHLORIDE VALUE (PPM)
Elkton Area	6,976	336	1/55	18.65	26.04	+7.39	275	237
Hastings Area	6,336	357	1/27	15.81	17.80	+1.99	696	424
Orange Mills Area	4,673	336	1/33	17.11	21.09	+3.98	513	428
Bunnell Area	27,793	309	1/305	9.29	10.23	+0.94	993	804
Miscellaneous Agricultural Wells *	---	276	---	16.55	22.78	+6.23	249	206
Perimeter Observation Wells *	---		---	30.75	32.58	+1.83	197	226

* See FIGURE 14 for definition of these locations.

If Y is related to only one independent variable X, and the relation is non-linear, a higher order polynomial model given by the following equation may be used to describe the relationship between Y and X

$$Y = C_o + C_1X + C_2X^2 + C_3X^3 + \ldots \quad (2)$$

It was assumed that chloride concentration is a function of one or more of the three independent variables, namely, potentiometric level (X_1), aquifer penetration (X_2), and well depth (X_3). Accordingly, regression analyses were performed by computer techniques to determine the relationship between the chloride concentration and the above variables.

The values of R, the correlation coefficient, ranged from 0.4444 to 0.4808 for simple linear regression (Y on X_1), and 0.4735 to 0.5201 for multiple regression (Table 2). These low values of R against a desired value of 0.9 or greater indicate that although chloride concentration may be significantly related to potentiometric level or aquifer penetration of well and depth of well in conjunction with potentiometric level, these independent variables as a group do not substantially account for chloride concentration in water pumped in different locations in the study area.

Regression analyses were also performed using a higher order polynomial model (Equation 2) with the potentiometric level as the polynomial, X. However, the quadratic and cubic models were not found to be better than the linear models as indicated by the values of R (Table 3).

The regression equations in the form of

$$Y = C_o + C_1X$$

where

X = potentiometric level

Y = chloride concentration

C_o = the Y intercept

C_1 = slope of the line

are shown in Table 4 for the four study months--March 1975, July 1975, September 1975, and May 1976.

In addition, regression analyses were performed using data collected during all study months from the wells in each specific area. Y was regressed on X_1, and the regression was found to be significant for Hastings, Orange Mills, and Bunnell areas. The results of the analysis are summarized in Table 5 and illustrated in Figure 15.

TABLE 2. -- Values of Correlation Coefficient in Linear Regression Analysis (All Wells in Area)

	Y (chloride concentration) is linearly related to			
Study Month	X_1	X_1 and X_2	X_1 and X_3	X_1, X_2, and X_3
Mar. 1975	0.4444	0.4762	0.4735	0.4771
July 1975	0.4589	0.5026	0.4975	0.5026
Sept. 1975	0.4808	0.5198	0.5125	0.5201
May 1976	0.4516	0.4828	0.4860	0.4840

where: X_1 = potentiometric level

X_2 = aquifer penetration of well

X_3 = depth of well

TABLE 3. -- Values of Correlation Coefficient in Regression With Higher Order Polynomial Models (All Wells in Area)

	Form of the Model		
Study Month	$Y=Co+C_1X$	$Y=Co+C_1X+C_2X^2$	$Y=Co+C_1X+C_2X^2+C_3X^3$
Mar. 1975	0.4444	0.4953	0.5001
July 1975	0.4589	0.5024	0.5029
Sept. 1975	0.4808	0.5283	0.5294
May 1976	0.4516	0.5149	0.5306

where: Y = chloride concentration

X_1 = potentiometric level

X_2 = aquifer penetration of well

X_3 = well depth

TABLE 4. -- The 'Best' Regression Equations (All Wells in Area) (X = Potentiometric Level)

Study Month	No. of Observations	Regression Equation
Mar. 1975	75	y=847.77-23.03x
July 1975	84	y=818.64-21.91x
Sept. 1975	95	y=844.41-22.21x
May 1976	78	y=875.49-24.40x
All above	332	y=846.13-22.82x

TABLE 5. -- Results of Regression Analysis for Different Study Areas (X = Potentiometric Level)

Study Area	No. of Observations	Regression Equation	Correlation Coefficient
Hastings	76	y=2042.34-89.88x	.3881
Orange Mills	88	y=1095.30-33.23x	.4118
Bunnell	39	y=1046.85-24.72x	.3709
*Elkton	10	--------	---

*Insufficient Data Points

Finally, regression analyses (chloride concentration on potentiometric level) were performed on all individual wells for which the number of observations available was greater than or equal to five. There were 44 such wells in the study area, and regression was found to be significant in 11 wells (Table 6). For these wells, the value of R ranged from 0.6425 to 0.9574, a significantly large value compared to the values found in the foregoing cases.

With regard to the use of regression equations derived in this study, the values of the correlation coefficients (R) for the regression equations were very low compared to a desired minimum value of 0.9. Hence, chloride values based on these equations will be very approximate; and therefore, these equations may not be used except for obtaining a rough estimate of the chlorides in the study area.

Distribution of Chlorides in Wells

The chloride data were fit to log normal and gamma distributions in order to generalize the distribution of different magnitudes of chloride concentration

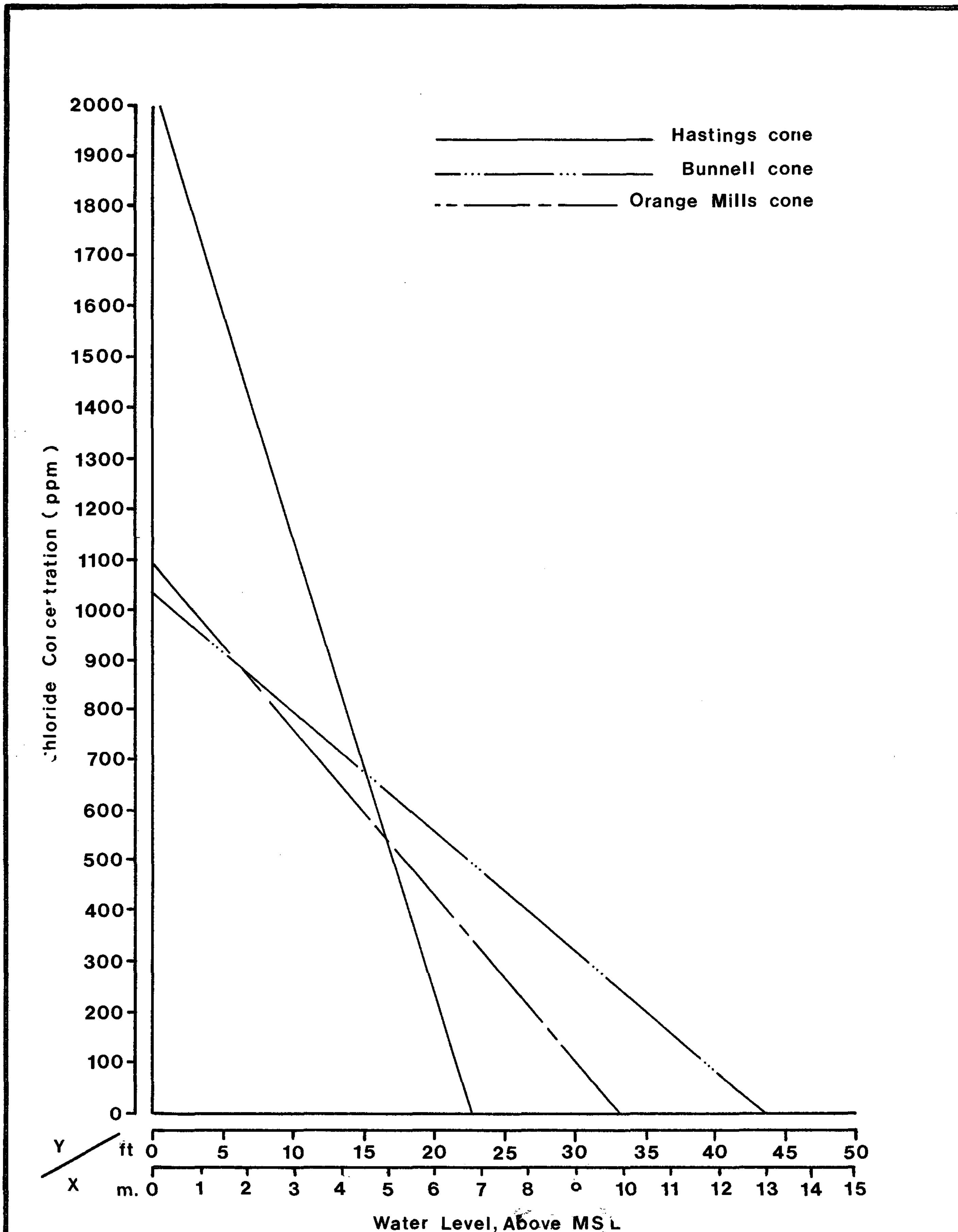


FIGURE 15. -- Derived Linear Equations of All Data from Individual Areas

TABLE 6. -- Results of Regression Analysis for Individual Wells (Chloride Concentration vs. Water Level)

LOCAL WELL NO.		CORRELATION COEFFICIENT(R)	GOODNESS OF FIT(R^2)	F STATISTIC	DEGREES OF FREEDOM	REMARKS*
Bu	66	.05	.0025	.0176	8	X
	101	.7079	.5011	6.0261	7	S
	126	.3267	.1067	.8365	8	X
	133	.5617	.3155	1.3826	4	X
El	267	.4938	.2438	.9673	4	X
	286	.0965	.0093	.0282	4	X
	388	.2729	.0745	.2414	4	X
Ha	31	.7469	.5620	7.6975	7	S
	76	.8706	.7579	9.3913	4	S
	226	.6440	.4148	4.2526	7	X
	263	.8671	.7518	15.1451	6	S
	378	.9574	.9166	43.9410	5	S
Or	68	.9202	.8467	16.5743	4	S
	69	.9286	.8623	18.7889	4	S
	77	.2095	.0439	.3215	8	X
	107	.4983	.2483	2.3120	8	X
	178	.4809	.2313	1.8053	7	X
	333	.6346	.4024	4.7187	8	X
Pe	2	.0229	.0005	.0016	4	X
	3	.1714	.0294	.0908	4	X
	4	.0124	.0002	.0006	5	X
	20	.0989	.0098	.0296	4	X
	134	.6425	.4128	5.6245	9	S
	290	.6648	.4420	4.7523	7	X
	306	.1398	.0196	.0598	4	X
	401	.7814	.6105	4.7023	4	X
	413	.5489	.3013	1.2935	4	X
	416	.5951	.3541	1.6450	4	X
	418	.0153	.0002	.0007	4	X
	422	.7953	.6324	5.1617	4	X
	427	.8167	.6670	6.0102	4	X
	432	.5677	.3223	3.8047	9	X
	433	.8764	.7681	9.9364	4	S
	436	.0392	.0015	.0046	4	X
	438	.1668	.0278	.0858	4	X
Mi	10	.7972	.6355	8.745	6	S
	26	.5437	.2956	2.9377	8	X
	76	.6248	.3904	1.9210	4	X
	92	.8820	.7780	10.5124	4	S
	108	.2207	.0487	.3583	8	X
	111	.3188	.1017	.5658	6	X
	133	.1083	.0117	.0712	7	X
	395	.3112	.0968	.3217	4	X

*S = Regression significant
X = Regression not significant

occurring in the wells of the study area. If these data are approximated by one of the theoretical probability distributions (Rao, 1978), it will permit drawing certain inferences such as what percentage of wells on the average will have a chloride concentration greater than a given magnitude, or what is the highest chloride concentration expected in a given percentage of wells.

The analysis showed that the chloride data closely fit a gamma distribution given by the following equation:

$$f(K) = \frac{a}{\Gamma(b)} (ak)^{b-1} e^{-ak} \quad (k > o); \tag{1}$$

where a and b are the parameters of the distribution.

The mean (μ), variance (σ_x^2), and the coefficient of skewness (γ_x) of the gamma distribution are given by the following equations:

$$\mu_x = b/a \tag{2}$$

$$\sigma_x^2 = b/a^2 \tag{3}$$

$$\gamma_x = 2.0/\sqrt{a} \tag{4}$$

For the study months of March 1975, July 1975, September 1975, and May 1976, the chloride data were fit to the gamma distribution by the method of maximum likelihood. (The study month of September 1976 was excluded from this analysis because of inadequate data.) Detailed information concerning gamma distribution may be found in Technical Memorandum No. 2, Supplemental Data for Report of "Saline Contamination of a Limestone Aquifer By Connate Intrusion in Agricultural Areas of St. Johns, Putnam, and Flagler Counties, Northeast Florida," St. Johns River Water Management District, July 1979.

Table 7 summarizes the data. Column A represents the chloride concentration that 50 percent of the wells will be less than or equal to, and column B represents the chloride concentration that 10 percent of the wells will be greater than or equal to.

TABLE 7. -- Expected Chloride Concentrations from Wells Throughout the Study Area for the Months of March, July, and September 1975 and May 1976

Study Month	Chloride Concentration in ppm A(50% of Wells ≤)	B(10% of Wells ≥)	Parameters of the Gamma Distribution (Equation 1) a, b
Mar. 1975	205	912	0.6748
July 1975	191	795	0.7252
Sept. 1975	210	778	0.8415
May 1976	208	837	0.7557

The data presented in Table 7 also allows for the predictability of the range in chloride concentration and the number of wells affected during any study month. It can be assumed that chloride concentrations may range in value between those limits established by those months used in the gamma distribution. The most significant indicator evolving from Table 7 is the value of 912 ppm chloride in column B. If, in fact, 10 percent of the total number of wells in the study area will exceed 912 ppm chloride during the month of March, the total number of wells which may be having a deleterious effect on the ground water resource could number in excess of 120.

Isochlor and Potentiometric Maps

As a graphic representation of water quality and potentiometric levels, a series of maps were constructed from the well data collected during the months of March, July, and September 1975, and May and September 1976. These maps, Figures 16 through 25, can be used to delineate specific areas of varying water quality and changing water levels in conjunction with regional and seasonal trends. Maps constructed from data collected during March 1975 and May 1976 were representative of low potentiometric levels encountered during the agricultural pumping season. On a regional basis, May also denotes the time for low potentiometric levels in the Floridan aquifer. Maps constructed from data of September 1975 and 1976 illustrate the highest potentiometric levels for the Floridan aquifer during the study period.

Several hydrologic features were observed during all sampling periods; although in some instances, the areal extent of these features varied seasonally. A cone of depression defined by the 10 feet msl potentiometric contour during the entire study was present in the vicinity of Haw Creek, southwest of Bunnell, presumably due to the thinning of the confining unit causing continual natural discharge of ground water to the Haw Creek system. During the pumping season, the size of the cone increased considerably to include the agricultural area to the west of Bunnell. A two to three feet rise in potentiometric level was observed in the Bunnell cone from March to September 1975.

In the agricultural areas of Hastings and Orange Mills, two cones of depression and associated areas of saline contamination were present during March 1975. By September 1975, water levels in the Hastings area had recovered approximately 8.5 feet; and in the Orange Mills area, water levels had risen almost 4.5 feet above the low level which occurred in March 1975. During May 1976, the areas of contamination were still present although there was a marked decrease in ground water withdrawals, and a defined cone of depression was not apparent. Similarly, in the Elkton vicinity, a cone of depression was present in March 1975, but absent in May 1976. Water level changes in Elkton were of the magnitude of approximately 4 feet to almost 7.5 feet in the center of the cone of depression. However, despite the range of fluctuations, the water quality in the Elkton area remained relatively unchanged throughout the year due to the thicker sequence of the Floridan aquifer and the higher transmissivity of the aquifer.

On a regional basis, water levels and quality in the potential recharge areas of Northeast Florida and Crescent City remain essentially uniform at all times. In those areas not affected by agricultural pumping, the potentiometric surface fluctuated at the most approximately 1.5 feet, and these changes were restricted to areas east of the St. Johns River. In general, an inland shift of the potentiometric contours in conjunction with increased chloride concentration was apparent only during the agricultural growing season.

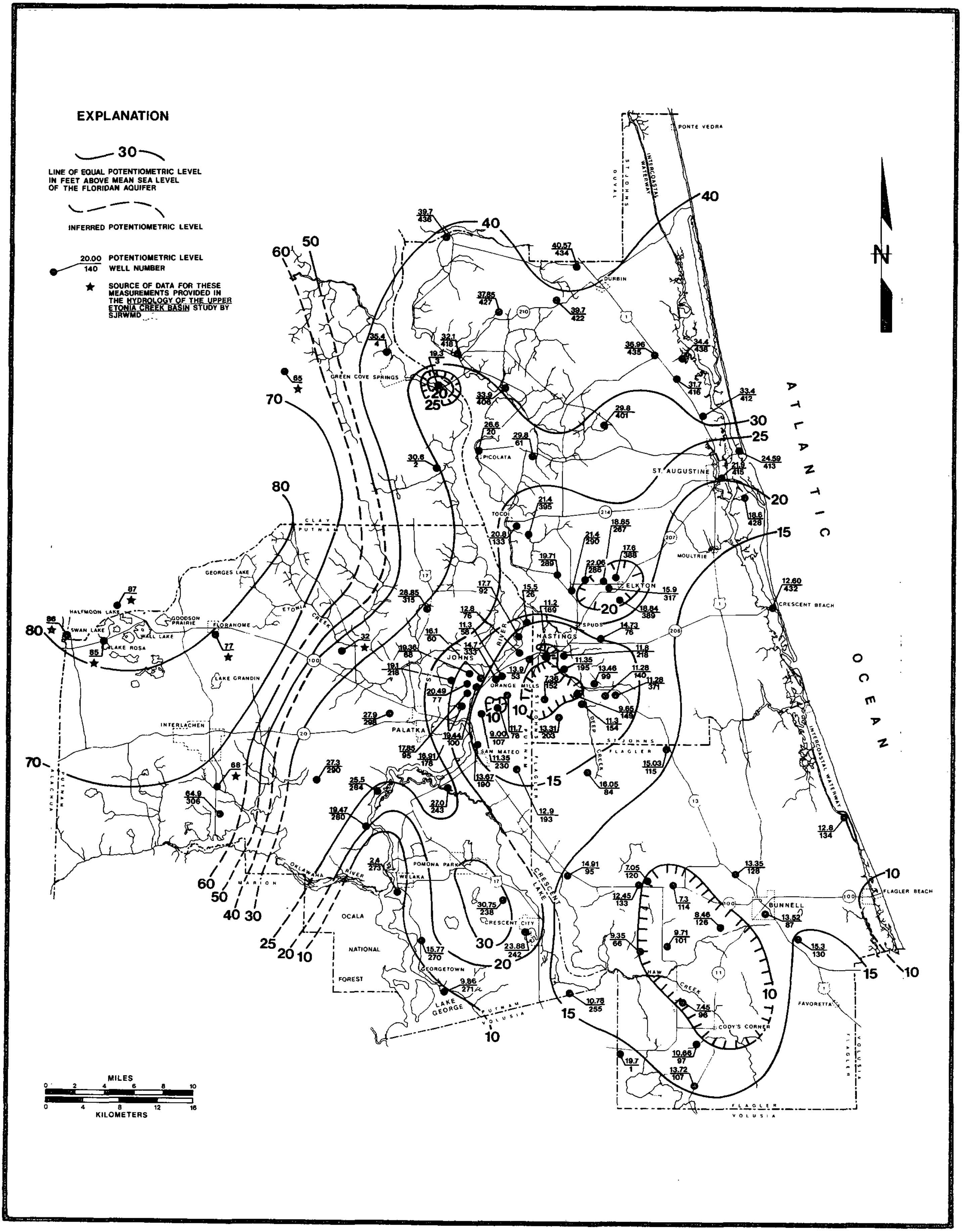


FIGURE 16. -- Potentiometric Level of the Floridan Aquifer, March 1975

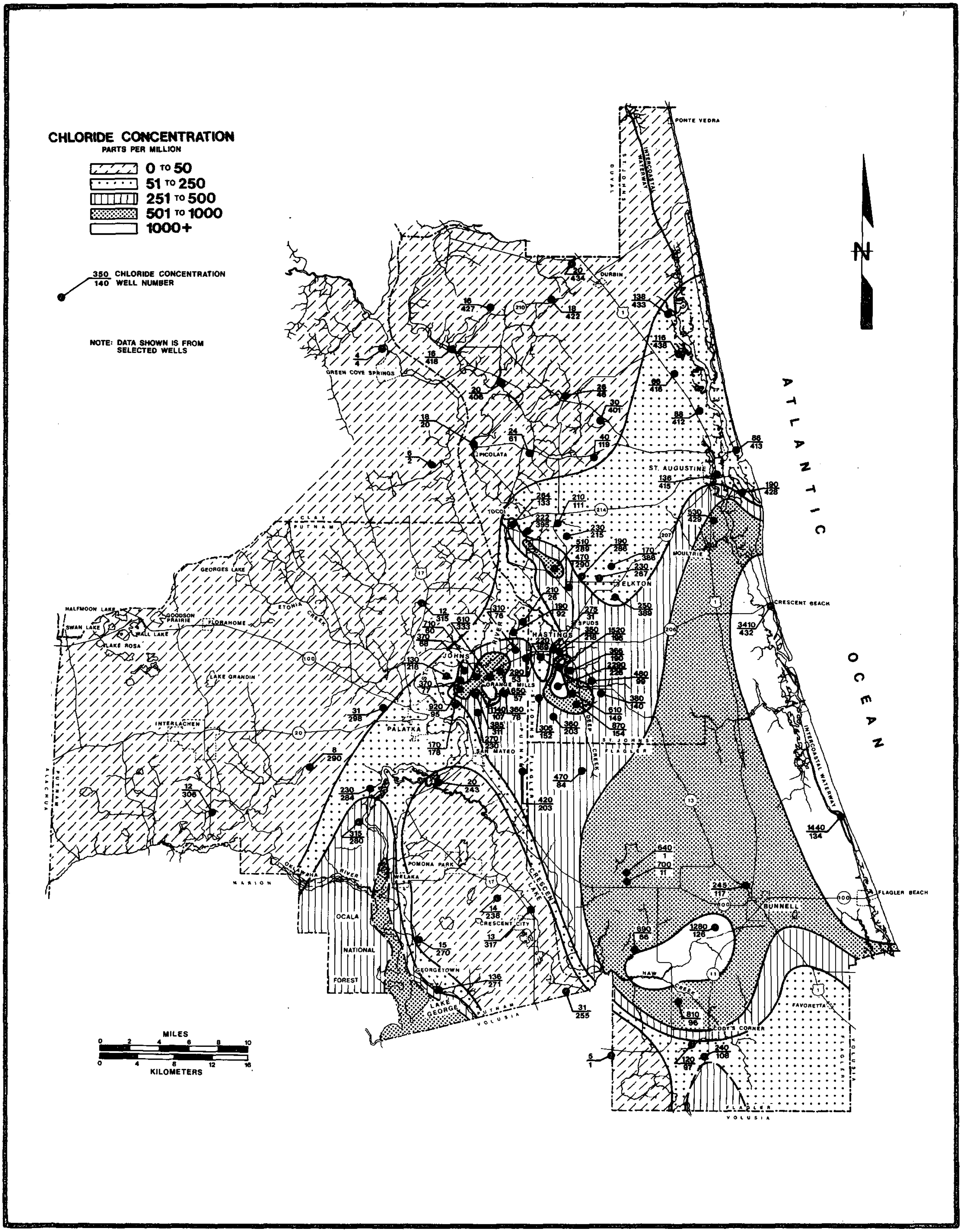


FIGURE 17. -- Isochlor Map of the Floridan Aquifer, March 1975

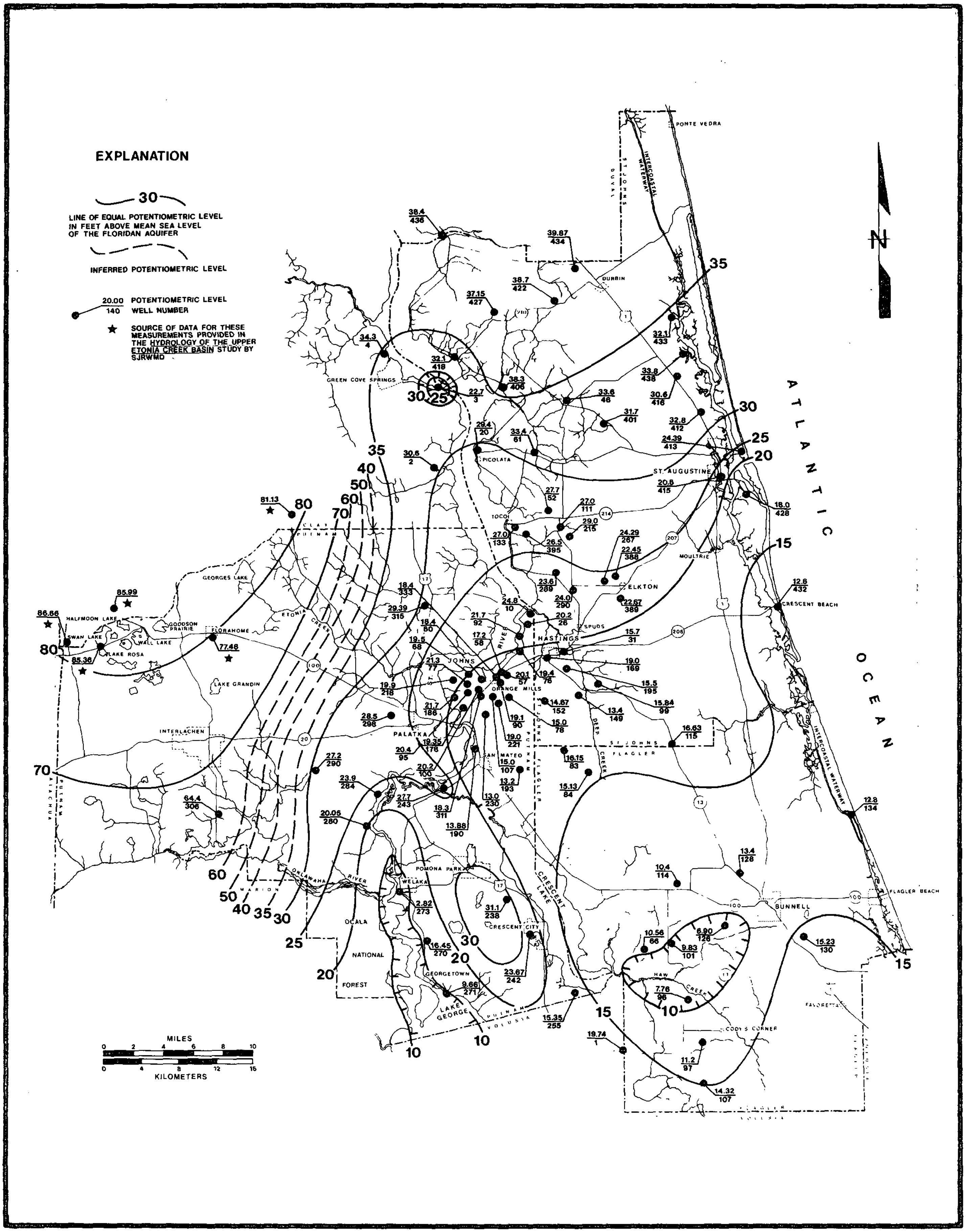


FIGURE 18. -- Potentiometric Level of the Floridan Aquifer, July 1975

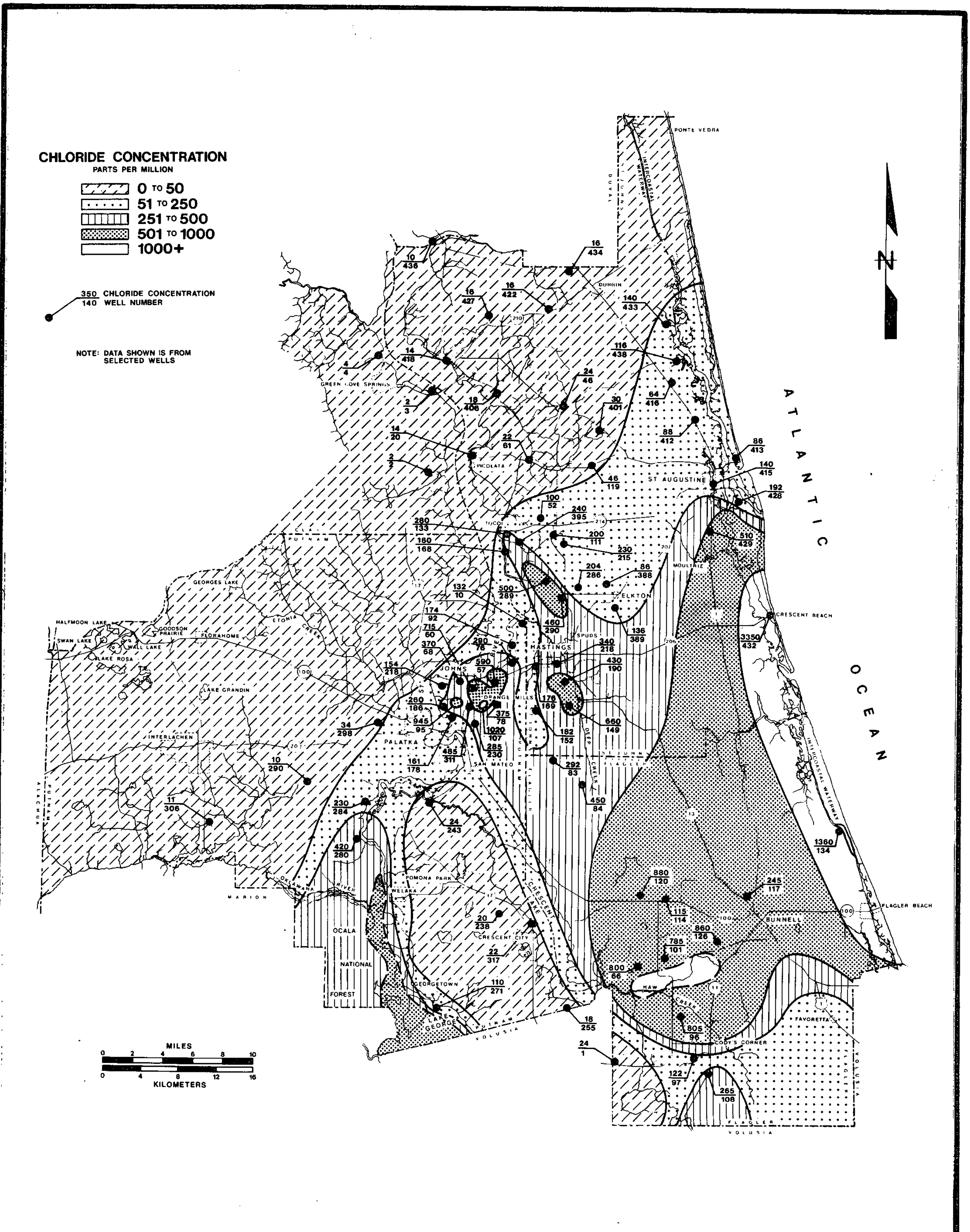


FIGURE 19. -- Isochlor Map of the Floridan Aquifer, July 1975

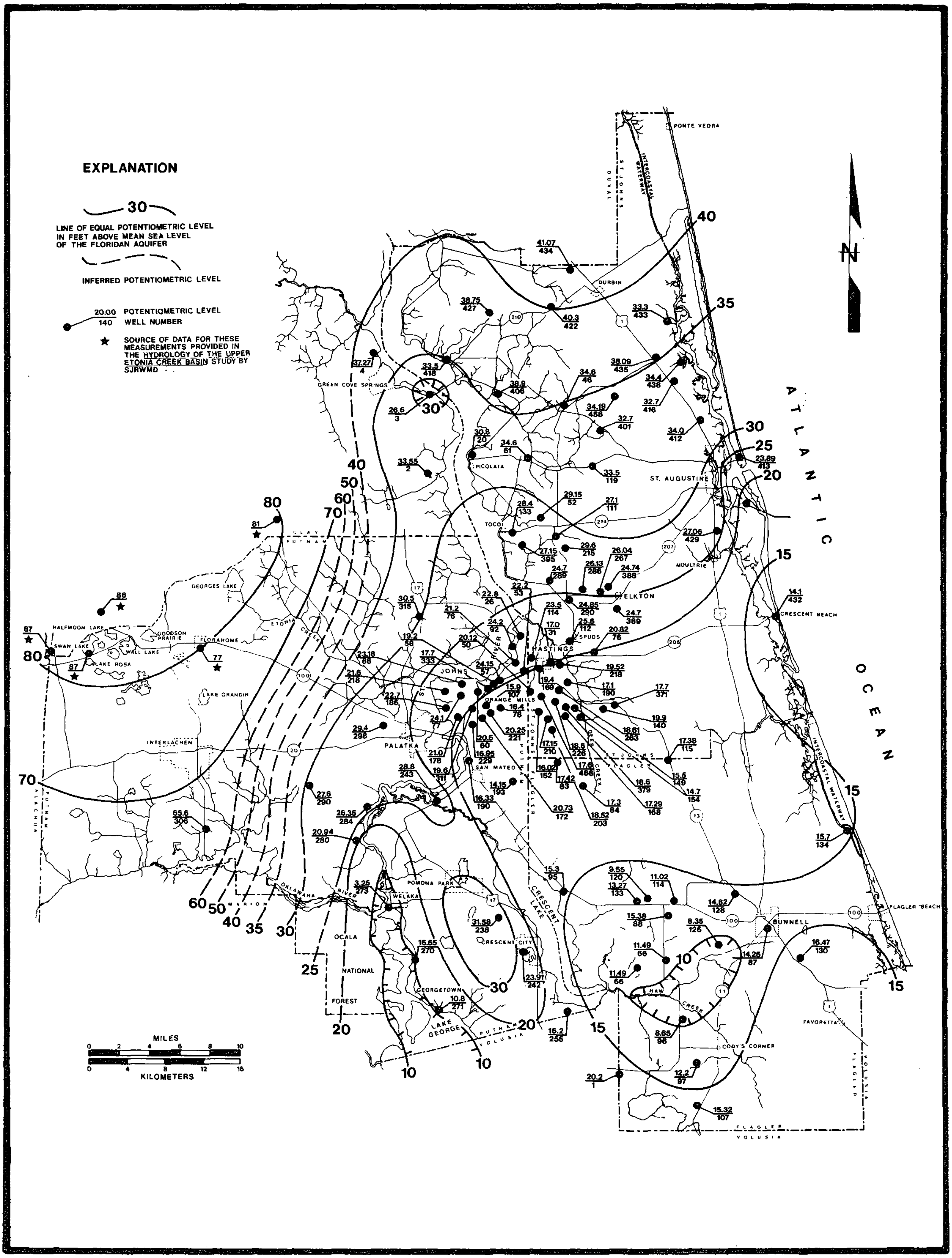


FIGURE 20. -- Potentiometric Level of the Floridan Aquifer, September 1975

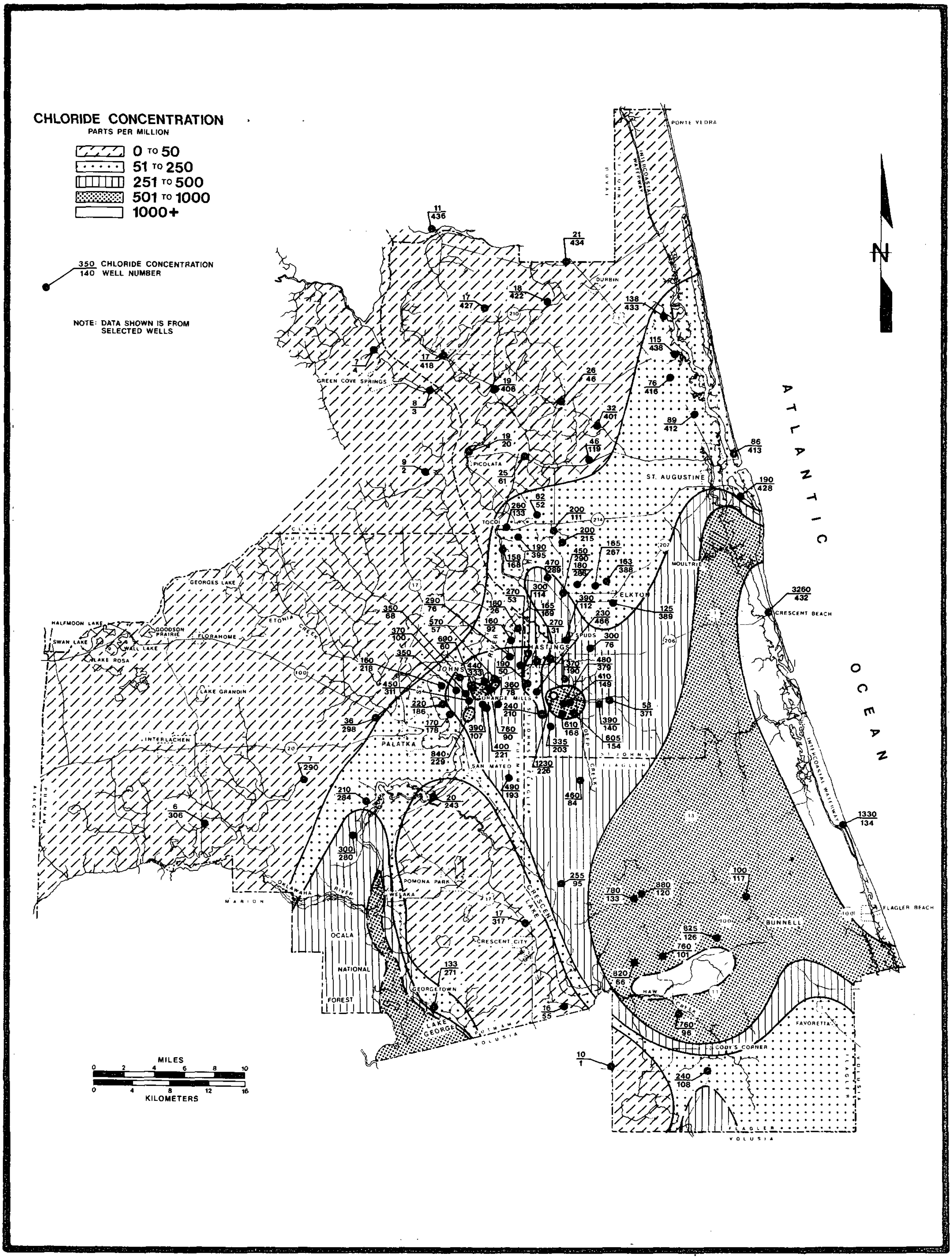


FIGURE 21. -- Isochlor Map of the Floridan Aquifer, September 1975

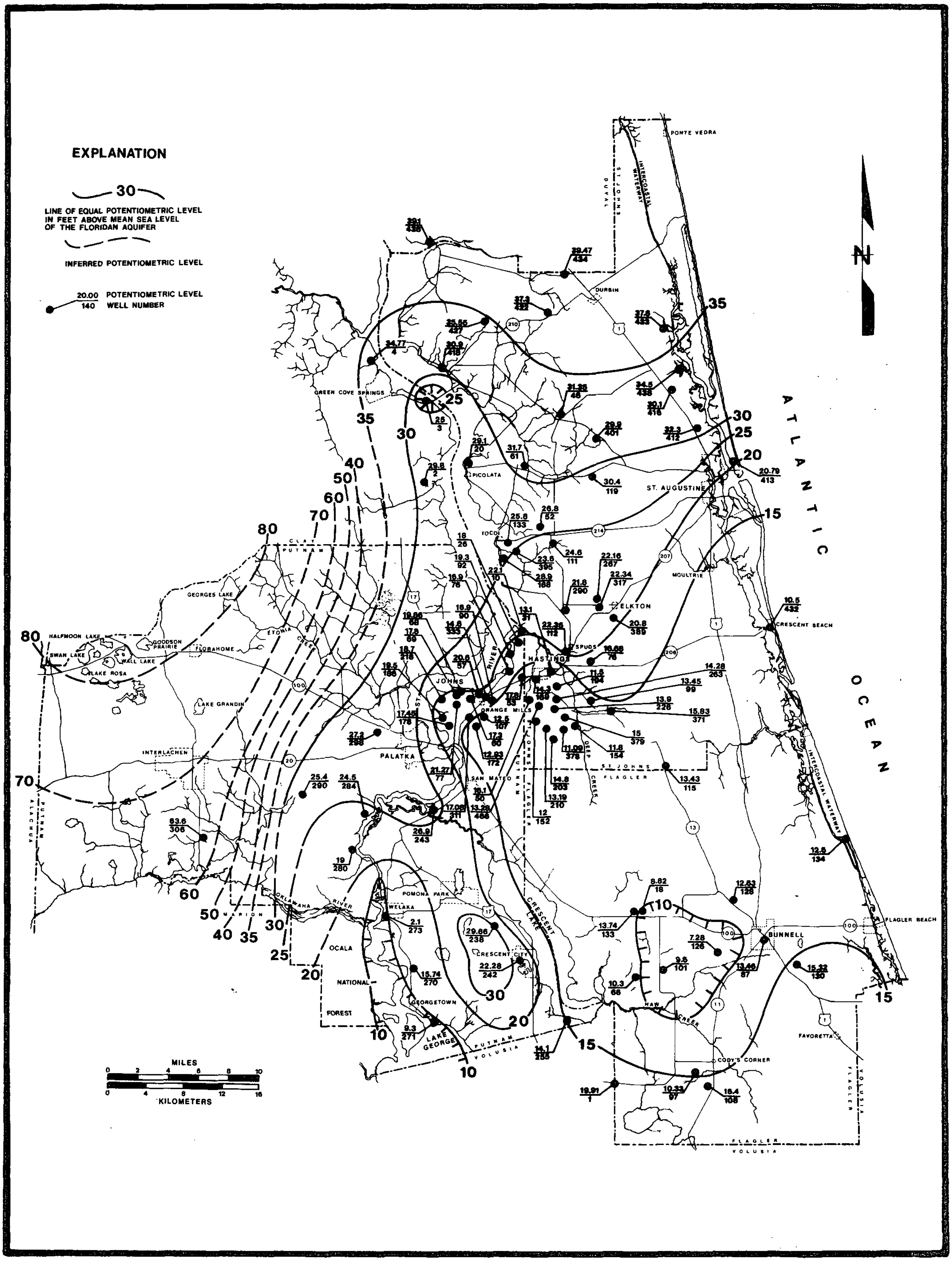


FIGURE 22. -- Potentiometric Level of the Floridan Aquifer, May 1976

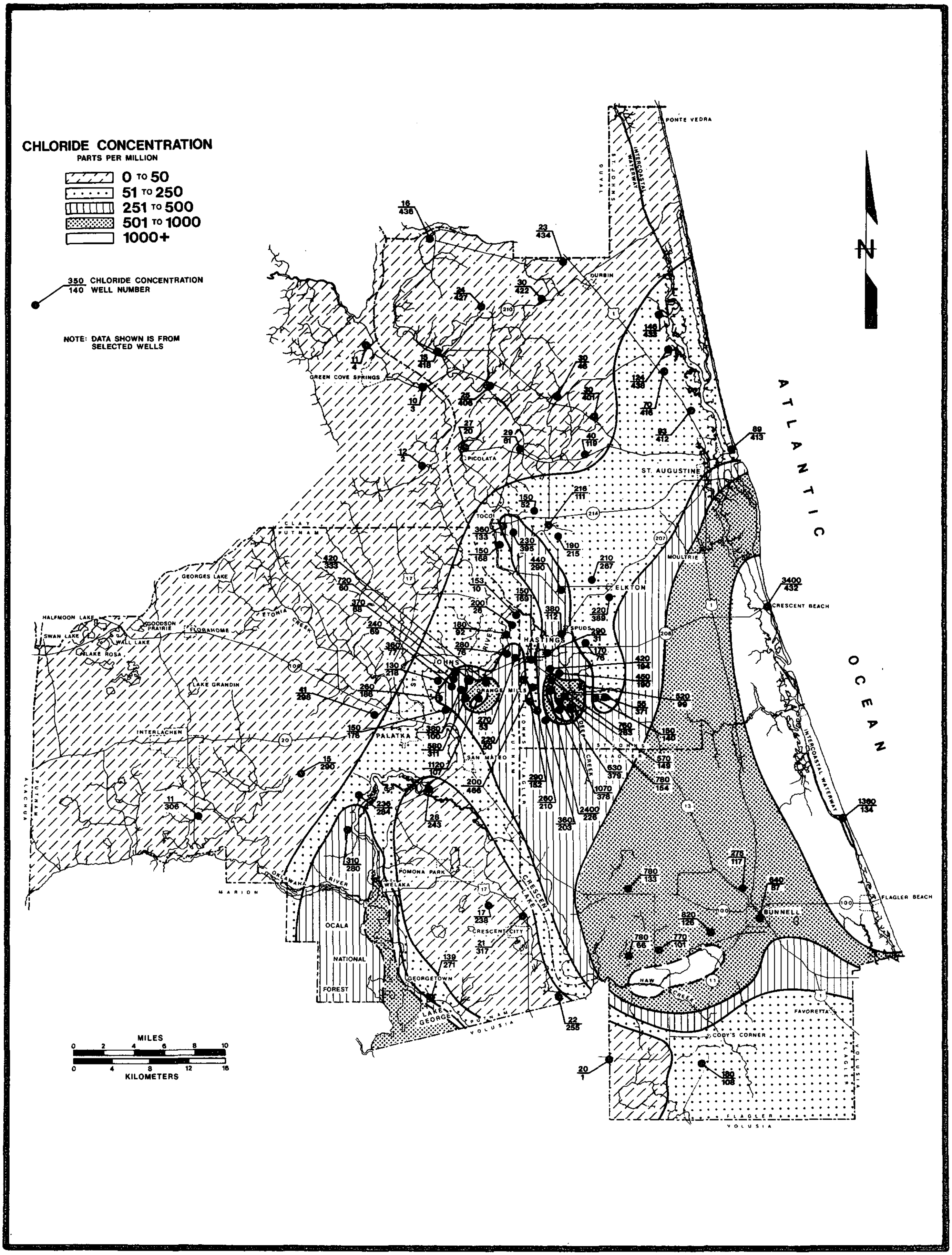


FIGURE 23. -- Isochlor Map of the Floridan Aquifer, May 1976

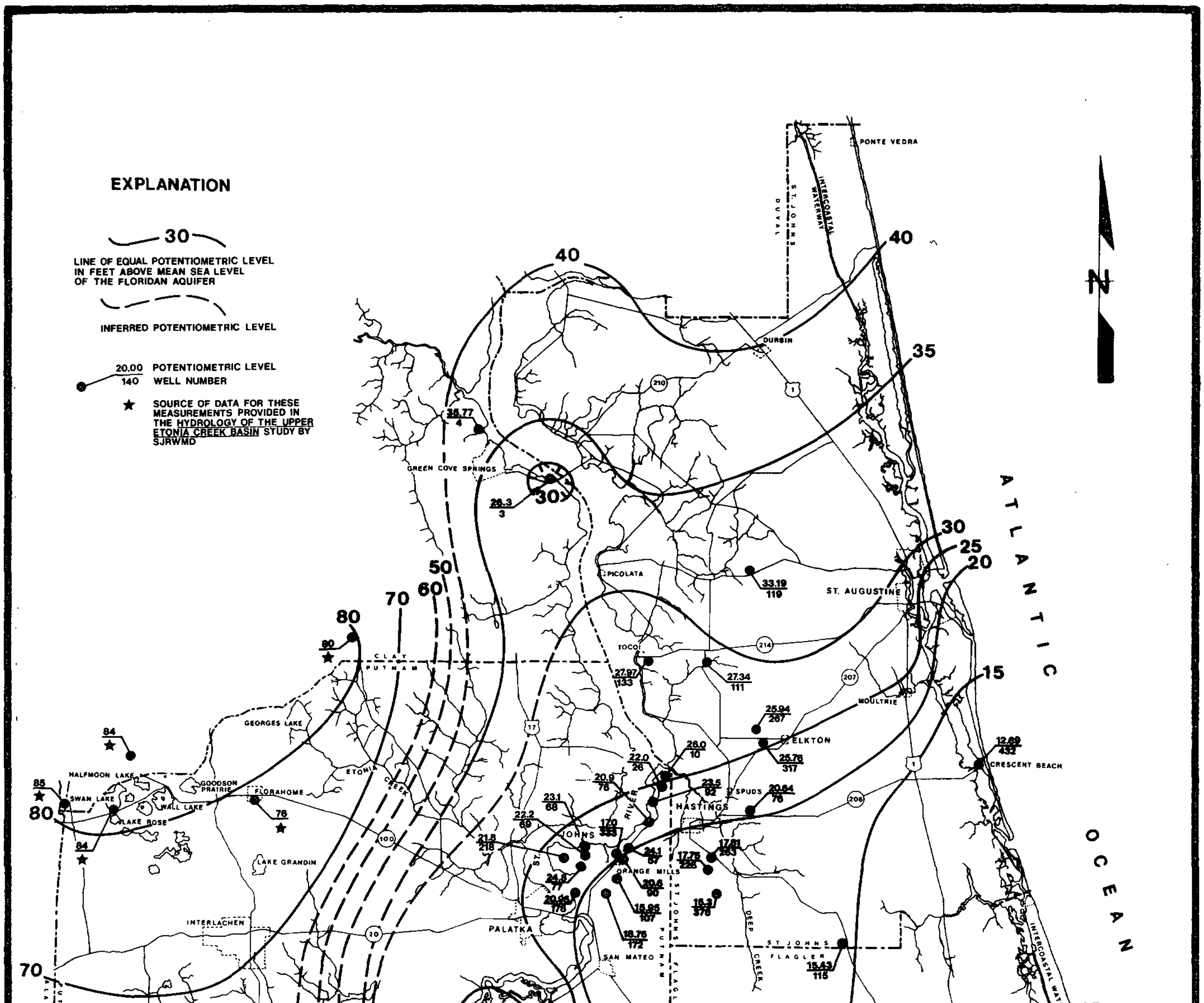


FIGURE 24. -- Potentiometric Level of the Floridan Aquifer, September 1976

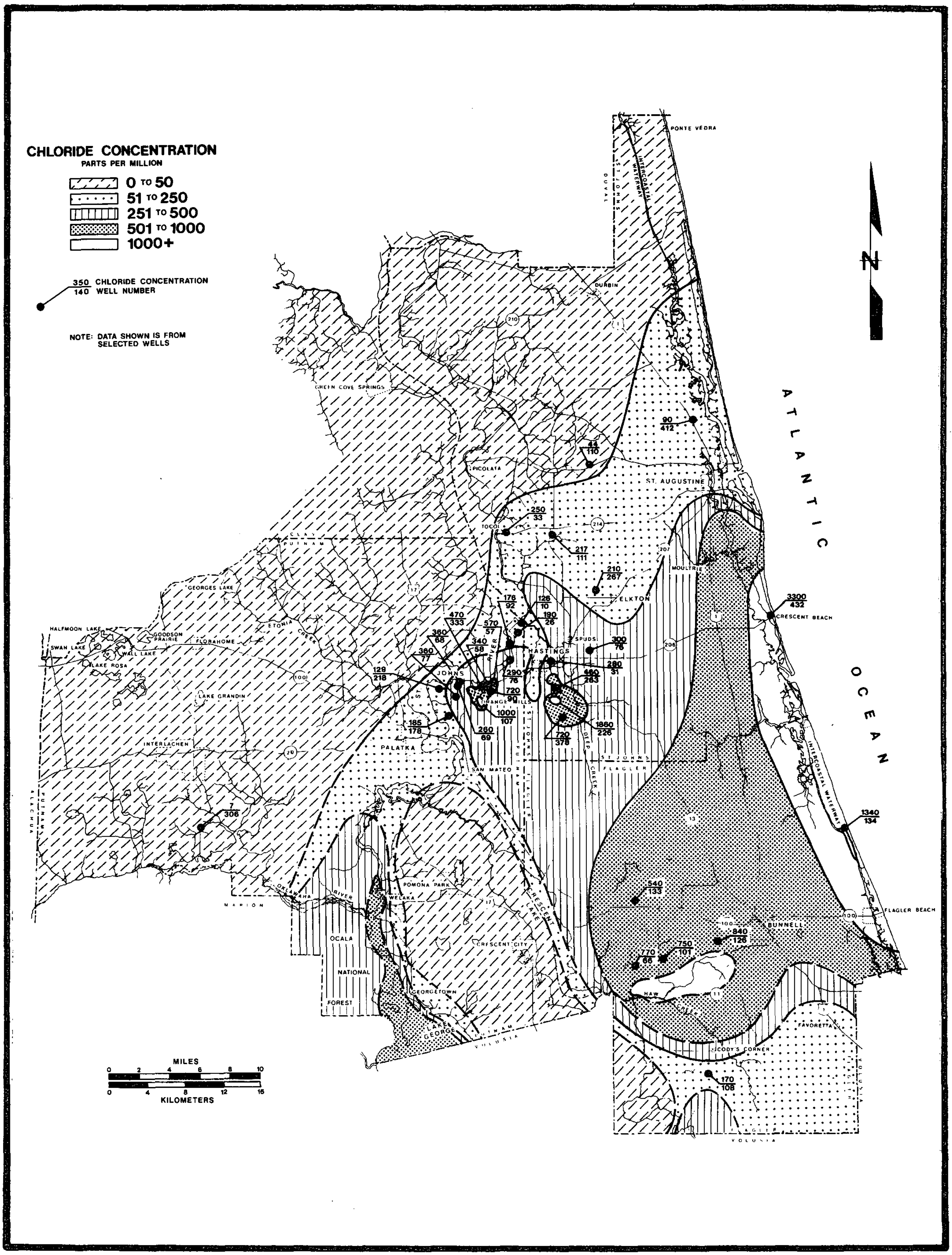


FIGURE 25. -- Isochlor Map of the Floridan Aquifer, September 1976

WATER USE

Agricultural water use in the project area begins in late September and extends through May during the growing of cabbage and potatoes. Prior to this study, only estimates of the average annual pumpage were available from local agricultural agencies. Because water meters are not usually installed on wells, the only way to account for the amount of water pumped during any given month was to utilize the electrical consumption records of local power companies.

Because of the density of irrigation wells and significant quantities of ground water withdrawals, the specific areas of Orange Mills, Hastings, Elkton, and Bunnell were inventoried. The inventory consisted of the location of the wells on the USGS seven and one-half minute topographic quadrangle maps and recording the electrical meter number, the motor's horsepower, the pump type (centrifugal or turbine), and the casing size. Fifty wells of various sizes and capacities were chosen at random and rated for discharge and electrical consumption by use of the revolving disc meter method (Anderson, 1973, p. 140). The data collected for rating discharge and electrical consumption were manipulated by computer analysis. The objectives of these analyses were (1) to determine gross amounts of monthly pumpage from the various areas and (2) to give the individual agriculturalist a method to determine quantitative monthly and annual irrigation use. For determining quantities of pumpage for individual water wells, refer to Technical Memorandum No. 2, Supplemental Data for Report of "Saline Contamination of a Limestone Aquifer by Connate Intrusion in Agricultural Areas of St. Johns, Putnam, and Flagler Counties, Northeast Florida", St. Johns River Water Management District, July 1979.

STATISTICAL BACKGROUND

Pump discharge and electrical consumption data were tabulated and sorted on the basis of casing size and electric motor horsepower. A regression was then performed on the data utilizing a computer program (Davis, 1973, p. 200). The analysis determined the relationship of energy input to the motor and the well's discharge. By utilizing a statistical program in the SJRWMD computer, a best-fit line was applied to the data by polynomial expansion (Davis, 1973, p. 207). The polynomial equations are applied to observations by the least square method or curvilinear regression analysis, and correlation coefficients derived. The correlation coefficients ranged from 0.801 to 0.995 for the kilowatt-discharge relationship and indicate a high measure of significance. The graph shown by Figure 26 represents the linear trend that exists between kilowatt input and discharge of various pump-motor combinations inventoried.

A second computer program was developed, utilizing equations that determine the power requirements for electrical motors (SCS, pp. 8-70), to calculate actual pumpage in gallons from monthly kilowatt-hour values. The program also calculates a value for the amount of kilowatt-hours it takes to produce 1,000 gallons of water. The KWH/1,000 gallon value derived was tested as to the type of statistical distribution the data characterized. The significance of the KWH/1,000 gallon value was determined by using the Chi-Square test (Davis, 1973, p. 119). If the KWH/1,000 gallon value showed an acceptable distribution with some level of significance, the mean of all the KWH/1,000 gallon values calculated could be applied to the total amount of monthly electrical usage in the four cones of depression to determine approximate monthly water pumpage in million gallons per day.

The distribution of the KWH/1,000 gallon values calculated by the program for all samples is represented by Figure 27. This type of distribution is known

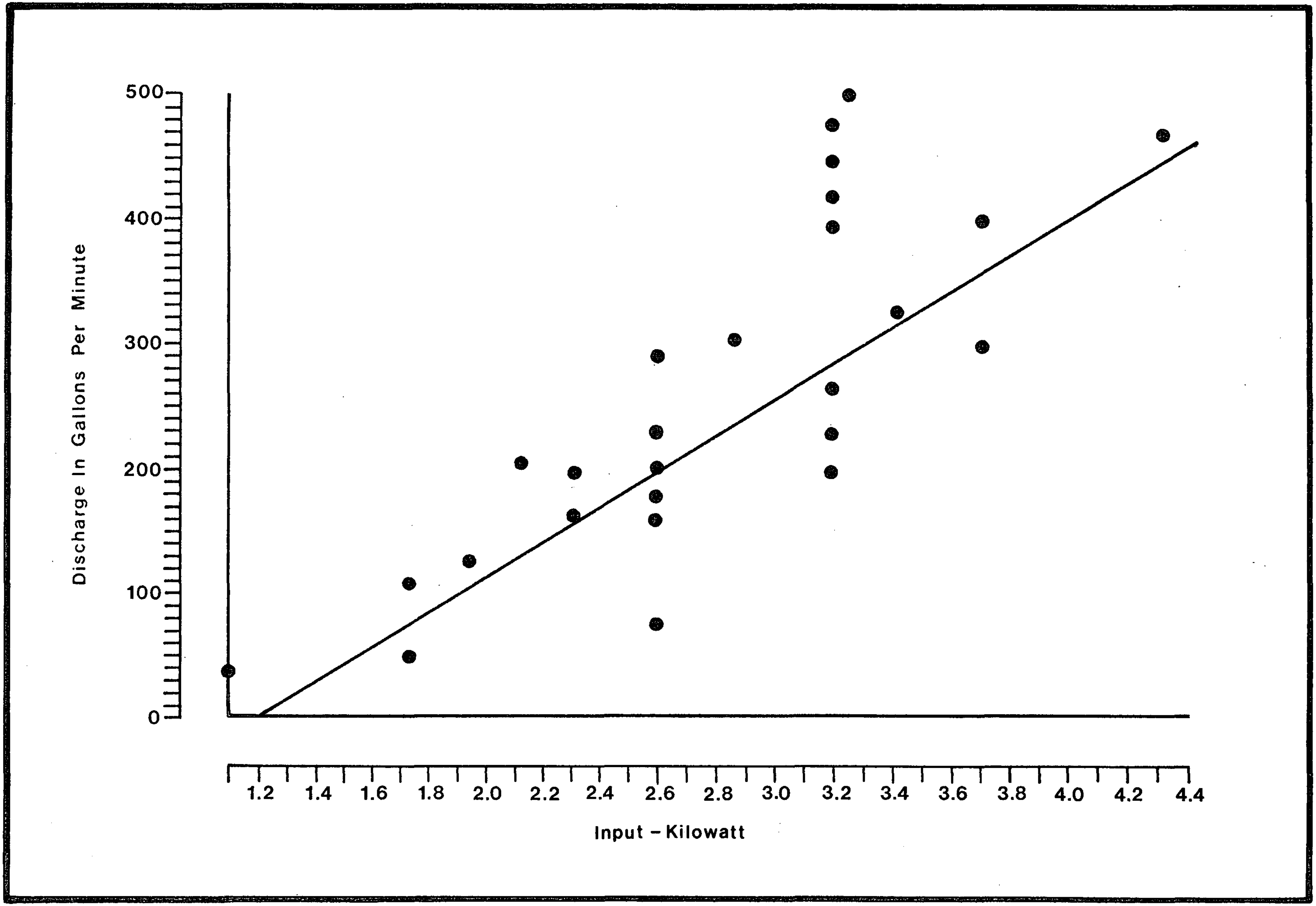


FIGURE 26. -- Generalized Trend of the Relationship Between Kilowatt Input and Discharge for Centrifugal Pumps Inventoried in the Tri-County Area

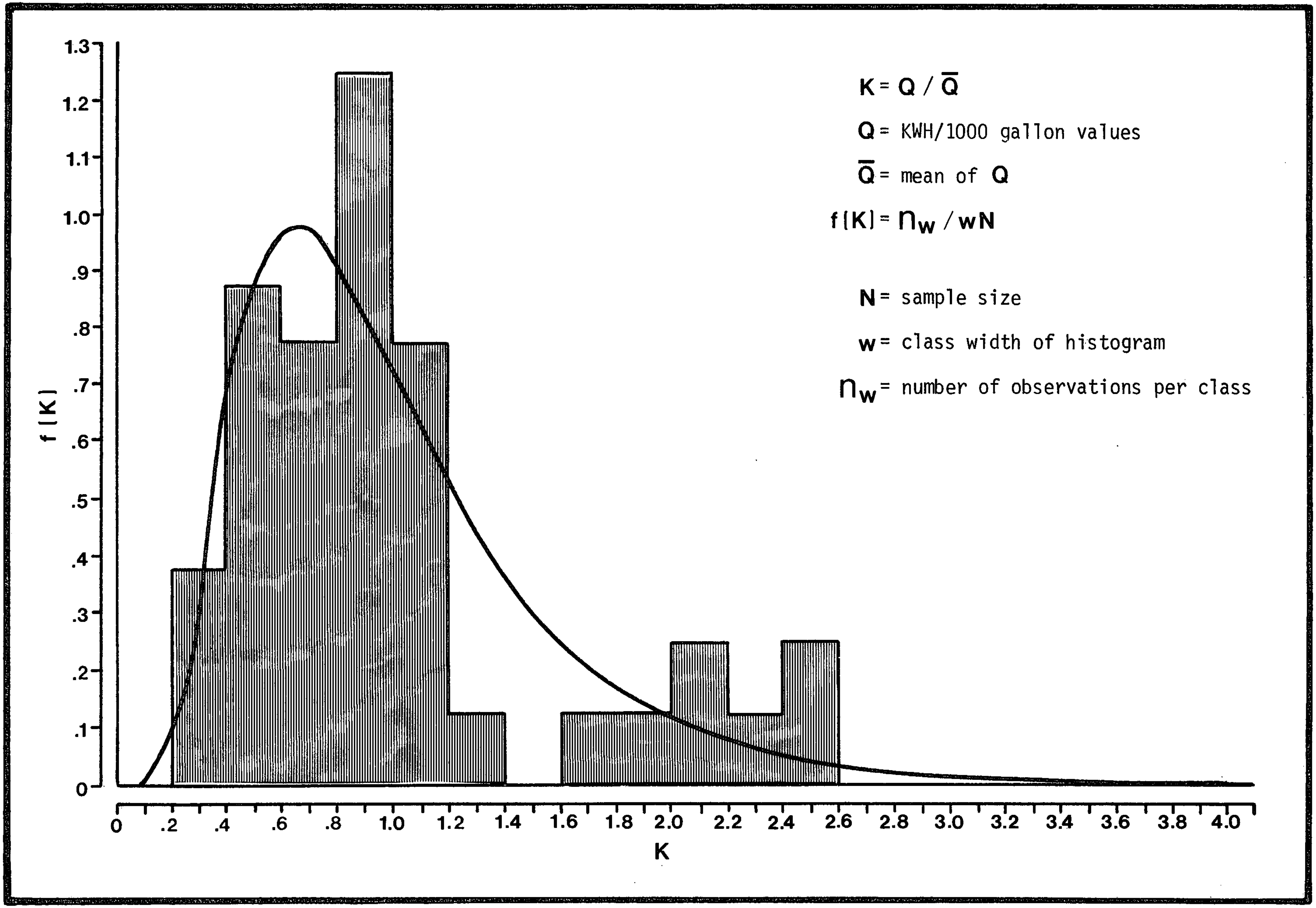


FIGURE 27. -- Log Normal Distribution and Histogram of Pump Data

as log normal. A log normal distribution is the density function of a variable whose logarithm adheres to the normal probability law. In this case, the parent population (all centrifugal irrigation pumps in the three counties) is log normally distributed. The distribution is skewed to the right and indicates a greater number of pumps encountered during the inventory had high electric consumption and low discharge. From the frequency data of the log normal analysis, it can be shown that of the irrigation pumps observed, 50 percent of the population fell below and 50 percent fell above the median value of 0.206 KWH/1,000 gallon value. The arithmetic mean was calculated at 0.238 KWH/1,000 gallons along with the mode being 0.155 KWH/1,000 gallons. In this case, equal consideration is given to all levels of pump operations to determine an overall value that can be applied to the electrical consumption data collected in order to determine local and regional ground water withdrawals. The mean value of .238 KWH/1,000 gallons best reflects those varying conditions which affect the pump's performance throughout the year.

To determine if the data had any statistical significance as a log normal population, the Chi-Square test procedure was utilized. The value calculated from the observed data by this procedure was 7.166 which fell below the critical value of 7.815 at 5 percent level of significance (Rohlf & Sokal, 1969, p. 164) with three degrees of freedom. Since the calculated value fell within the significant level, it can be assumed that the 0.238 KWH/1,000 gallon value is a valid number to be applied to the bulk of the electrically operated irrigation pumps in the study area.

GROUND WATER WITHDRAWALS

The earliest known estimates of ground water withdrawals for each county were prepared in 1956 (Florida Water Resources Study Commission, 1956). In

1965 the U. S. Geological Survey (Pride, 1970-1973), began preparing county reports of water use which were to be compiled every five years. These estimates were collected by Survey hydrologists who obtained specific information from the SCS and ASCS. In Table 8, the estimated historical ground water use for irrigated crops in Putnam, Flagler, and St. Johns counties is presented.

TABLE 8. -- Historical Ground Water Withdrawals for Irrigated Crops in Putnam, Flagler, and St. Johns Counties

COUNTIES	IRRIGATED ACRES	GROUND WATER WITHDRAWAL (MGD)
	1956	
Putnam	No Report	5
Flagler	4,000	6
St. Johns	16,000	26
	1965	
Putnam	13,000	11.6
Flagler	6,500	3.5
St. Johns	22,000	13.9
	1970	
Putnam	11,200	7.6
Flagler	8,230	9.0
St. Johns	19,000	22.1
	1975	
Putnam	11,380	15.8
Flagler	4,500	6.7
St. Johns	20,120	28.57

Utilizing the information obtained from the statistical portions of the Water Use section, ground water pumpage can be quantified for each inventoried intensive agricultural area. After determination of the withdrawals by the electrical consumption method for each cone, comparisons can be made to the county-wide pumpage estimates provided by local agents to the USGS for irrigated crops.

As previously mentioned, the extent of the growing season is approximately nine months beginning late September and continuing through May. Much of the irrigation during September, October, and early November is by natural artesian flow of wells located in the Orange Mills and Hastings areas. It was assumed that the water discharged during this time in the regions of artesian flow would be approximately equal to the pumpage for irrigation in Elkton and Bunnell. In the 1975-1976 growing season, the largest withdrawal rate occurred during March for the Bunnell and Hastings (Figure 28A, B) cones of depression areas. The Orange Mills and Elkton areas (Figure 28C, D) reach the highest withdrawal rate during April. Cumulatively, March (Figure 28E) was the highest month with a 36.25 MGD rate of withdrawal. Table 9 shows the average monthly and annual withdrawal rate in the four agricultural areas. In both cases, the Hastings area maintains a higher ground water withdrawal rate throughout the entire year due to the high density of irrigation wells within that locale.

In order to compare the water use values derived by the electrical consumption method, county water use figures collected from the agricultural agents were reduced to similar dimension in the specific areas of Bunnell, Elkton, Hastings, and Orange Mills. The individual agricultural areas were measured from topographic maps by planimeter, and the ratio between each specific area and the associated county irrigated acreage was determined (Table 10). Those values were used to calculate the ground water withdrawals (Table 11) for each

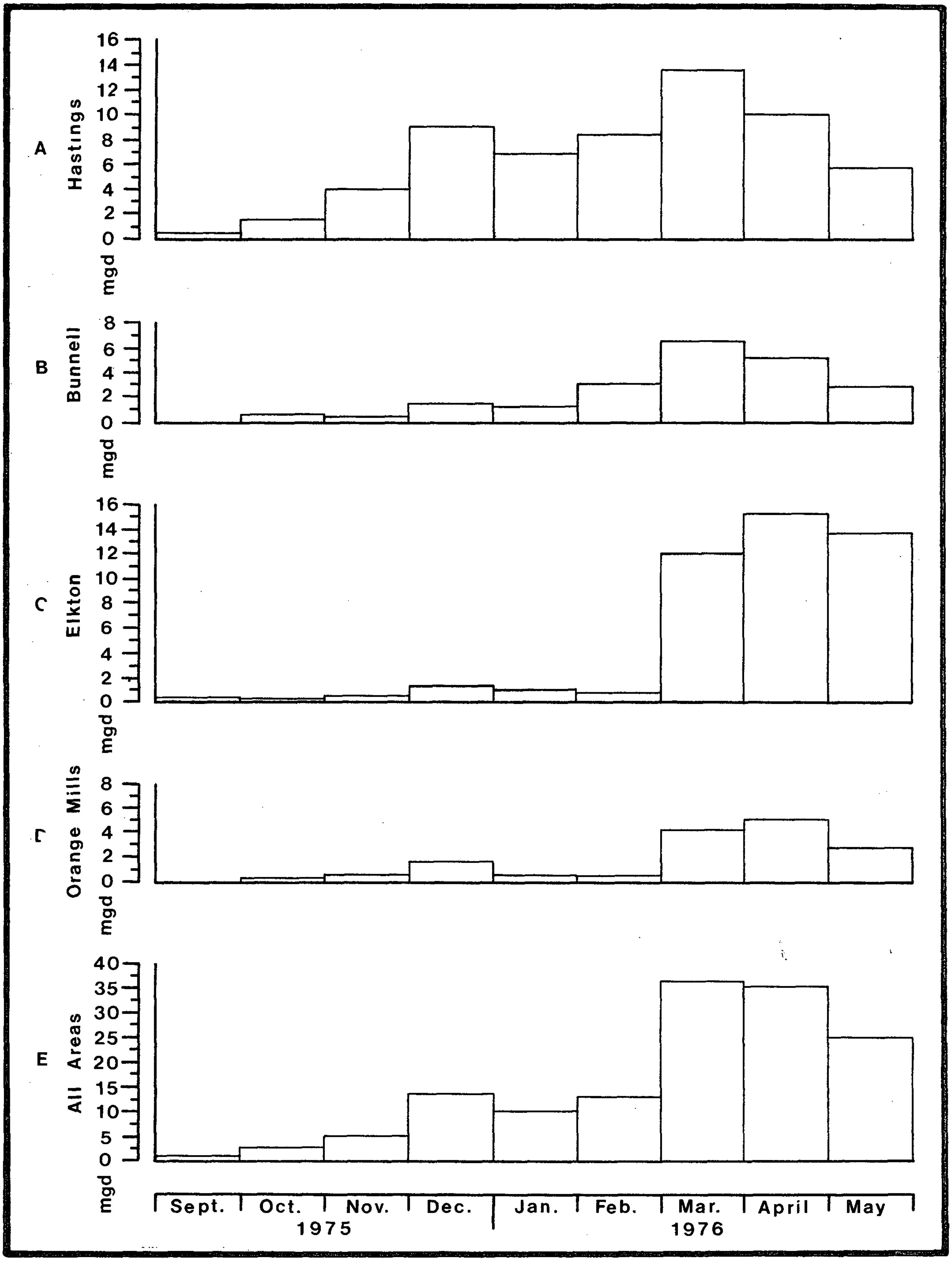


FIGURE 28. -- Ground Water Withdrawals for Individual Intensive Farming Areas 1975-1976

TABLE 9. -- Ground Water Withdrawal Rates for the Individual Farming Areas

Cone	Average Monthly Withdrawal Rate for Nine-month Growing Season (MGD)	Average Annual Withdrawal Rate (MGD)
Orange Mills	1.87	1.40
Hastings	6.58	4.93
Elkton	4.92	3.69
Bunnell	2.30	1.73

TABLE 10. -- The Percentages of Production from Each Cone Located Within Putnam, Flagler, and St. Johns Counties for Cabbage and Potatoes

<table>
<tr><th>Cone</th><th>Number of Wells Utilized</th><th>Area of Cones(Acre)</th><th>County-Wide Acres for Cabbage and Potatoes</th><th colspan="2">Percentage of Production Area/County</th></tr>
<tr><td>Orange Mills East Palatka (Putnam County)</td><td>48</td><td>4,673</td><td>9,300(est.)</td><td colspan="2">50%</td></tr>
<tr><td>Hastings (St. Johns County)</td><td>110</td><td>6,336</td><td rowspan="2">17,100</td><td>37%</td><td rowspan="2">78%</td></tr>
<tr><td>Elkton (St. Johns County)</td><td>82</td><td>6,976</td><td>41%</td></tr>
<tr><td>Bunnell (Flagler County)</td><td>74</td><td>27,793</td><td>5,032(est.)</td><td colspan="2">18%</td></tr>
</table>

specific area on the basis of the USGS Water Use Inventory Data (Leach, 1978). Table 12 compares the estimated 1975 water use inventory values to the figures derived by the electrical consumption method. The calculated values for the three counties are approximately 55 percent lower than the values estimated in the Water Use Inventory of 1975.

The apparent discrepancies in ground water withdrawal values obtained from the two methods arise from the criteria used in the determination. The data collected from the local agricultural agencies are estimates of the total irrigated acreage and an assumed average application rate for a particular crop type. The criteria used in the electrical consumption method considers the source and method of producing water for irrigation purposes. By utilizing electrical consumption records combined with well inventory data, withdrawals can be estimated with a higher degree of confidence.

Comparison of the pumpage values presented in Table 12 does not indicate that ground water withdrawals in the Tri-County area have decreased by 45 percent, but that another method to estimate pumpage may be more accurate. Although there are large differences between the two methods of estimating water use, the existing water quality problems in the area are real and measurable, regardless of which water use estimate is more accurate. Therefore, the importance of continually emphasizing water conservation practices and programs is needed.

TABLE 11. -- Comparison of the Annual Ground Water Withdrawal Rates for Each Cone as Calculated from the 1975 Water Use Inventory (USGS) and the Electrical Consumption Method for Cabbage and Potatoes

Cone	*Est. Withdrawals for 1975 (MGD)	Withdrawals Calculated by Electrical Consumption for 1975-76 Growing Season (MGD)	Est. Withdrawals by Artesian Flow (MGD)
Orange Mills East Palatka (Putnam)	3.2	1.40	0.31
Hastings (St. Johns)	7.34	4.93	1.80
Elkton (St. Johns)	8.14	3.69	----
Bunnell (Flagler)	5.65	1.73	----

*Taken from 1975 USGS Water Use Inventory.

TABLE 12. -- Comparison of County-Wide Ground Water Withdrawal Rates for Potatoes and Cabbage as Calculated from the 1975 Water Use Inventory (USGS) and the Electrical Consumption Method

County	*Withdrawals During 1975 (MGD)	Withdrawals Calculated by Electrical Consumption for 1975-76 (MGD)	Difference
Putnam	6.40	3.43	47%
St. Johns	25.45	13.36	48%
Flagler	5.65	1.73	69%

*Taken from 1975 USGS Water Use Inventory, Leach, 1978.

FLOW-NET ANALYSIS

In conjunction with the District's work in the Tri-County area, the U. S. Geological Survey under a cooperative agreement supplied supplemental information about the hydrogeologic characteristics of the Floridan aquifer specifically located in St. Johns, Putnam, and Flagler counties (Bentley, 1977). Data from 18 additional pump tests were added to the original data collected in 1956 (Bermes, Leve, Tarver, 1963) to achieve an area-wide distribution. The data collected provides the necessary information to calculate ground water withdrawals by flow-net analysis method. It also provides information needed to develop a predictive ground water model of the area in the future.

Ground water movement may be quantitatively determined by a method known as flow-net analysis (Ferris et al., 1962). From the flow-net map (Figure 29), amounts of withdrawals can be calculated by a modified form of the Darcy equation

$$T = \frac{Q_n}{IL}$$

where: T = coefficient of transmissivity in gpd/ft.

Q_n = rate of flow of water through a cross-section of aquifer in gallons per day (gpd)

I = hydraulic gradient in feet per mile

L = average width of cross-section of aquifer in miles

Figure 30 shows the relative transmissivity values for the project area that were used in the flow-net analysis (Bentley, 1977 and Bermes, Leve, Tarver, 1963). From the range of transmissivity (T) values observed throughout the three counties, the aquifer seems relatively homogeneous with an average T value of 285,000 gpd/ft. Transmissivities used in the calculation of ground water movement are averages of the values attained from various pump tests in each locale of the study area.

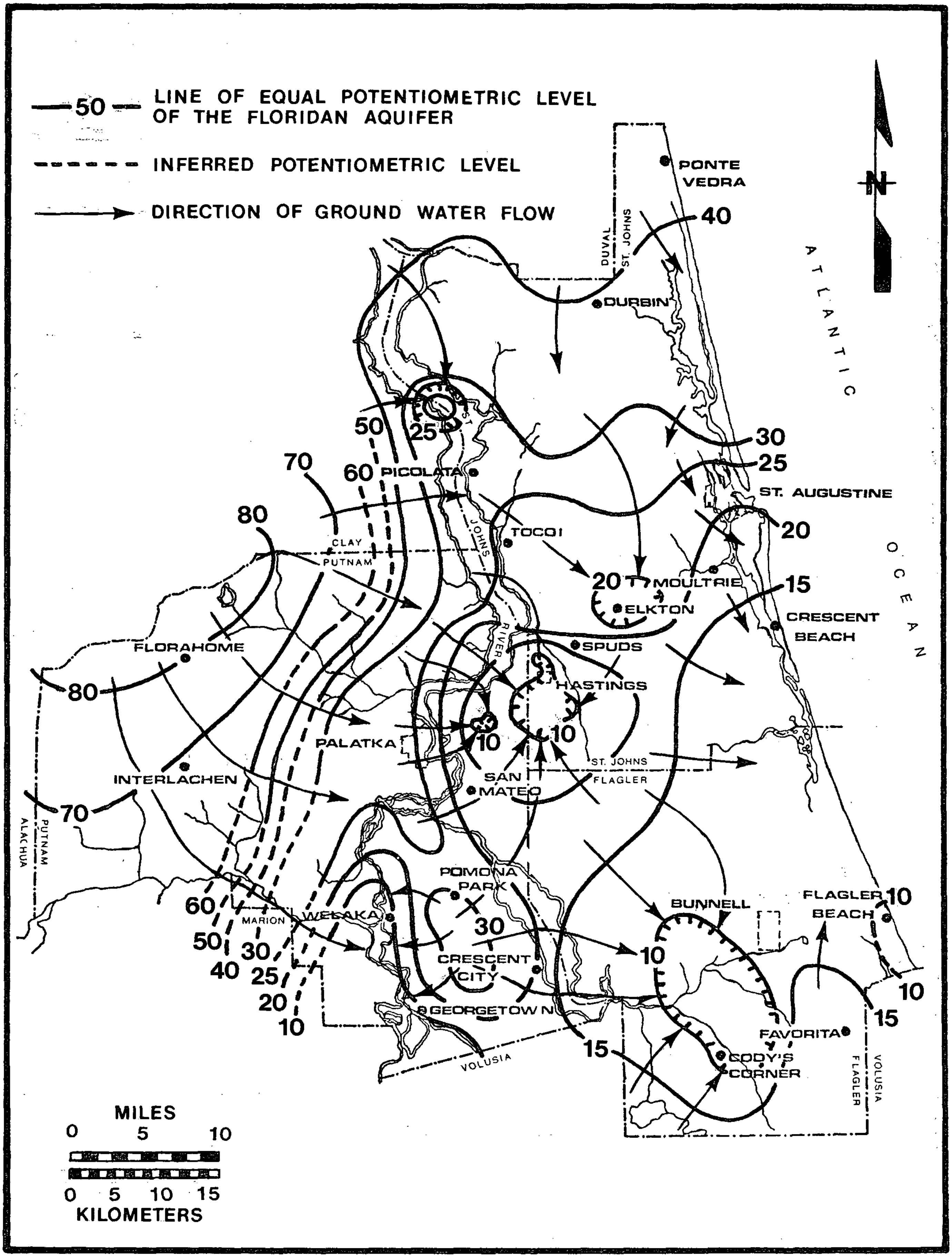


FIGURE 29. -- Potentiometric Level and Generalized Direction of Ground Water Movement Within the Tri-County Area, March 1975

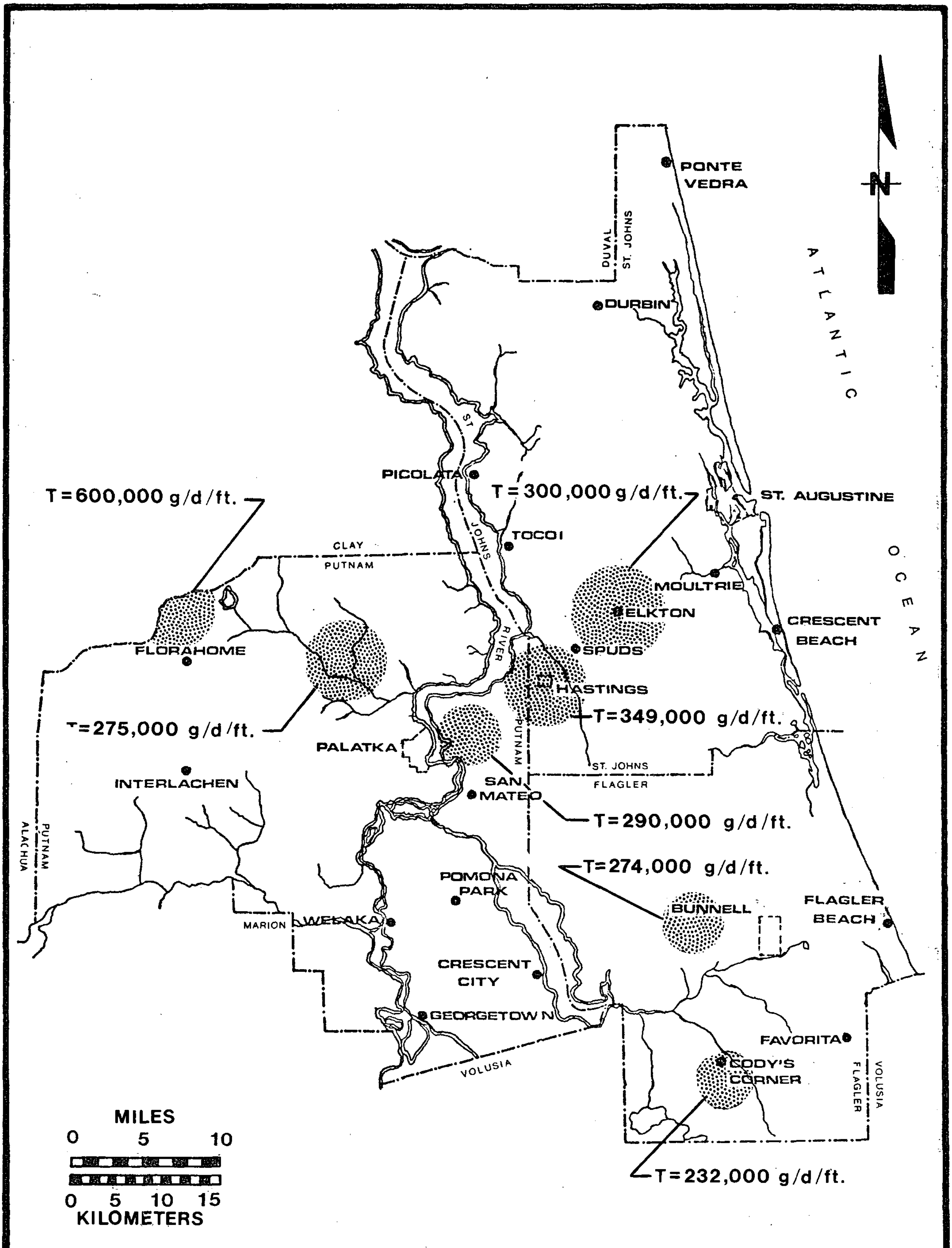


FIGURE 30. -- Average Transmissivity Values for the Floridan Aquifer in the Project Area (Modified from Bentley, 1977)

Using the March 1975 potentiometric levels, quantities of ground water inflow were calculated for the four cones of depression (Table 13). The values derived by flow-net analysis are compared to the values calculated from the electrical consumption method for the same month (Figure 31). The electrical consumption determination of ground water withdrawals in the Elkton cone were slightly higher than the flow-net value. The KWH quantities were slightly higher due to additional turbine pumps operating in the area. Under various conditions, these pumps may exceed the quantities of water produced by centrifugal pumps. However, from field observation, the turbine pumps consume electrical power at a higher rate than the 0.238 KWH/1,000 gallon value used in the analysis. This is reflected in the apparent slightly higher ground water withdrawals estimated for the Elkton cone.

Discharge calculated by flow-net method in the Bunnell cone is twice the water use determined from the electrical consumption method. The discrepancy in the two values can be attributed to the natural discharge of Floridan aquifer water within the Haw Creek Basin. The ever present cone of depression in the vicinity of the Creek during times of non-pumping suggests that discharge occurs. Natural discharge in the area is related to the thinning of the confining unit above the Floridan aquifer, which allows upward leakage of aquifer water to the creek and spring discharge along the creek and its tributaries.

TABLE 13. -- Values Used in the Flow-Net Analysis for Cones of Depression

Cone	Transmissivity gpd/ft	Hydraulic Gradient ft/mi (Contour Interval)	Width of Aquifer Cross Section mi	Quantity of Flow mgd
Orange Mills	290,000	2.69 (15-10)	6.00	4.68
Elkton	300,000	4.10 (20-15)	8.00	9.84
Bunnell	252,500	1.12 (15-10)	44.50	12.58
Hastings	349,000	1.53 (15-10)	25.75	13.75

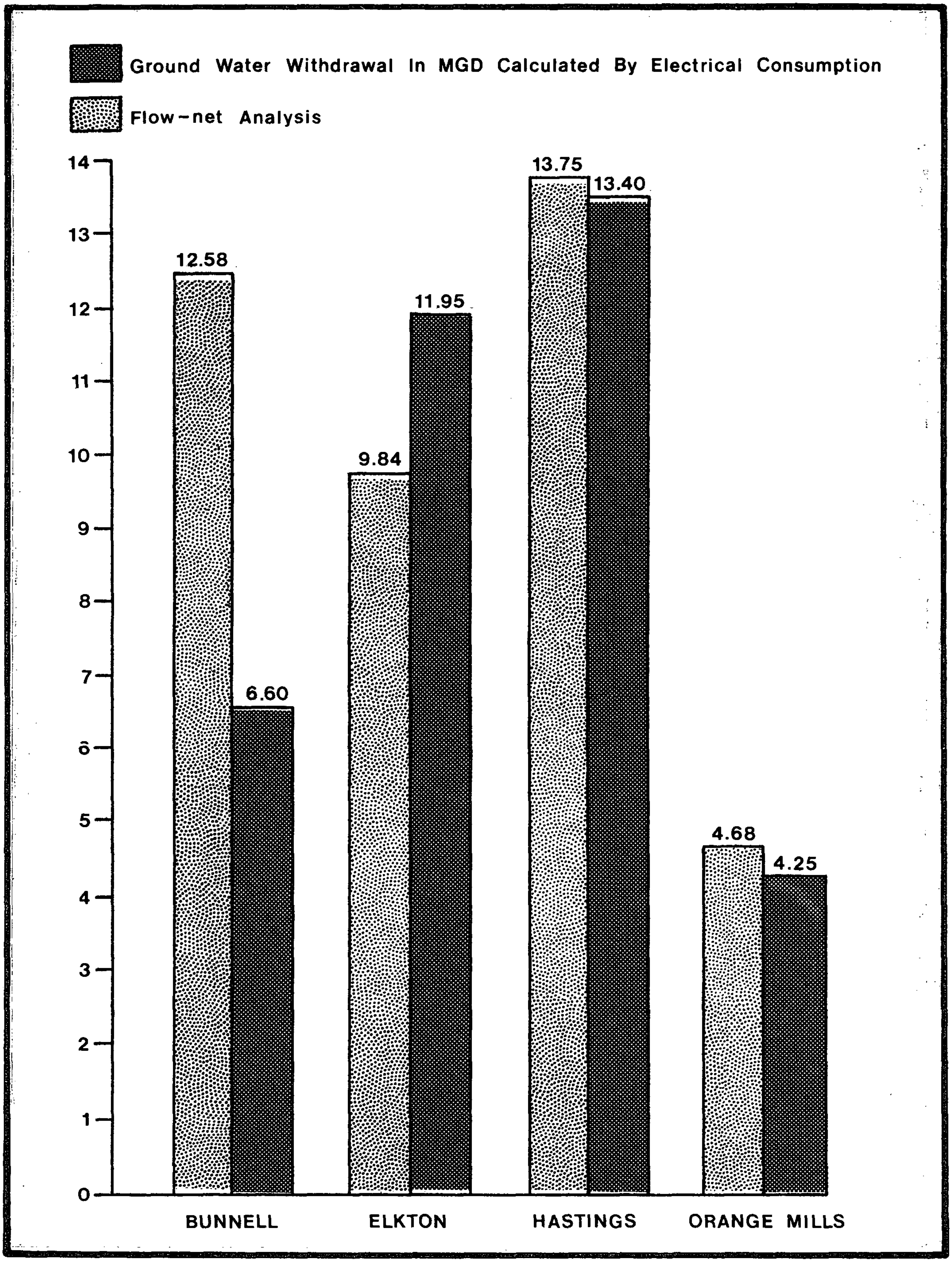


FIGURE 31. -- A Comparison of the Ground Water Withdrawals as Calculated by the Electrical Consumption Method and by Flow-Net Analysis

SALT WATER CONTAMINATION AND WELL CONSTRUCTION CHARACTERISTICS

WELL DEPTH

Early in the history of agricultural well construction within the Tri-County area, a common practice by many drillers was to penetrate the aquifer deeper than necessary. Overdeepening of these artesian wells was an attempt to obtain improved water quality and increased flow. Although contamination problems were not apparent at that time, the demand on the aquifer increased and water levels steadily declined, creating a quality and quantity problem. As the thickness of the fresh water zone was reduced, connate water slowly migrated upward into the fresher zones of the Floridan aquifer; and in the agricultural areas, deep artesian wells (Figure 32) have become direct means for contamination of the fresh upper zones of the Floridan aquifer.

After review of well data derived from Information Circular No. 37 and Report of Investigation No. 32 of the Florida Geological Survey and the 1970 Department of Natural Resources well inventory, the St. Johns River Water Management District Tri-County inventory was conducted in hopes of delineating maximum allowable well depth for individual cones of depression. The survey focused upon wells with chloride concentrations greater than 1,000 gpm. Although the U. S. Department of Agriculture recommends 500 ppm as the maximum allowable chloride concentration for potato and cabbage cultivation, local IFAS, SCS, and ASCS agents have indicated 1,000 ppm as a more realistic maximum value for seepage irrigation of these crops in the Tri-County agricultural area. They cite soil conditions and rainfall amount and frequency as the principal factors which allow the utilization of ground water with chloride concentrations in excess of the USDA maximum recommended limits.

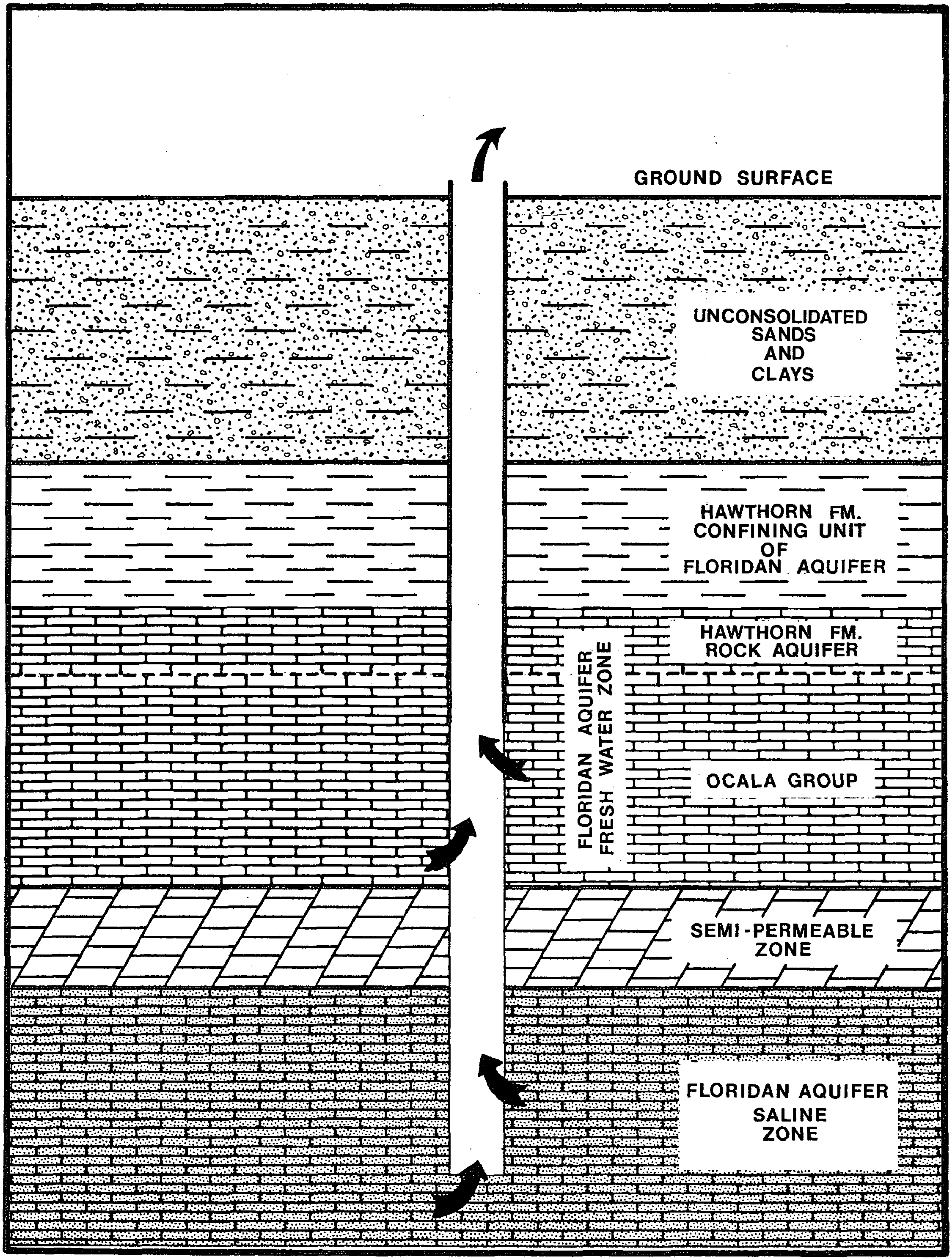


FIGURE 32. -- Diagram Showing the Contamination of the Fresh Zone Within the Floridan Aquifer from the Deeper Saline Zone

Table 14 portrays well depth information for wells with chloride concentrations greater than 1,000 ppm within the Tri-County agricultural area cones. An absence of wells with chloride concentrations greater than 1,000 ppm was noted within the Elkton area, and is probably due to an average 10-feet higher potentiometric level. All cones reflect a wide range of well depths which suggests the presence of varying hydrogeologic conditions within individual cones. Therefore, determination of a maximum allowable well depth for individual cones is not possible based solely upon the well depth criterion alone. Figure 33 indicates the location of the wells with chloride concentrations of greater than 1,000 ppm in Flagler, St. Johns, and Putnam counties. However, many irrigation wells have not been inventoried, and some wells were abandoned over a period of years. Many of the wells were allowed to flow uncontrolled for several years. Also, as wells were abandoned, they were not plugged or capped to meet State specifications. In several cases observed in the field, the well casing was cut below ground level; and the capped well was covered over by further cultivation.

TABLE 14. -- Well Depth Information for Wells in the Agricultural Cones of the Tri-County Area With Chloride Concentrations Greater Than 1,000 Parts Per Million

County	Cone	No. of Wells With Known Depth	Mean Well Depths (Ft.)	Range Well Depths (Ft.)	No. of Wells With Unknown Depth
St. Johns	Hastings	16	476	147-600	14
Putnam	Orange Mills	21	363	168-500	21
Flagler	Bunnell	18	351	100-520	18

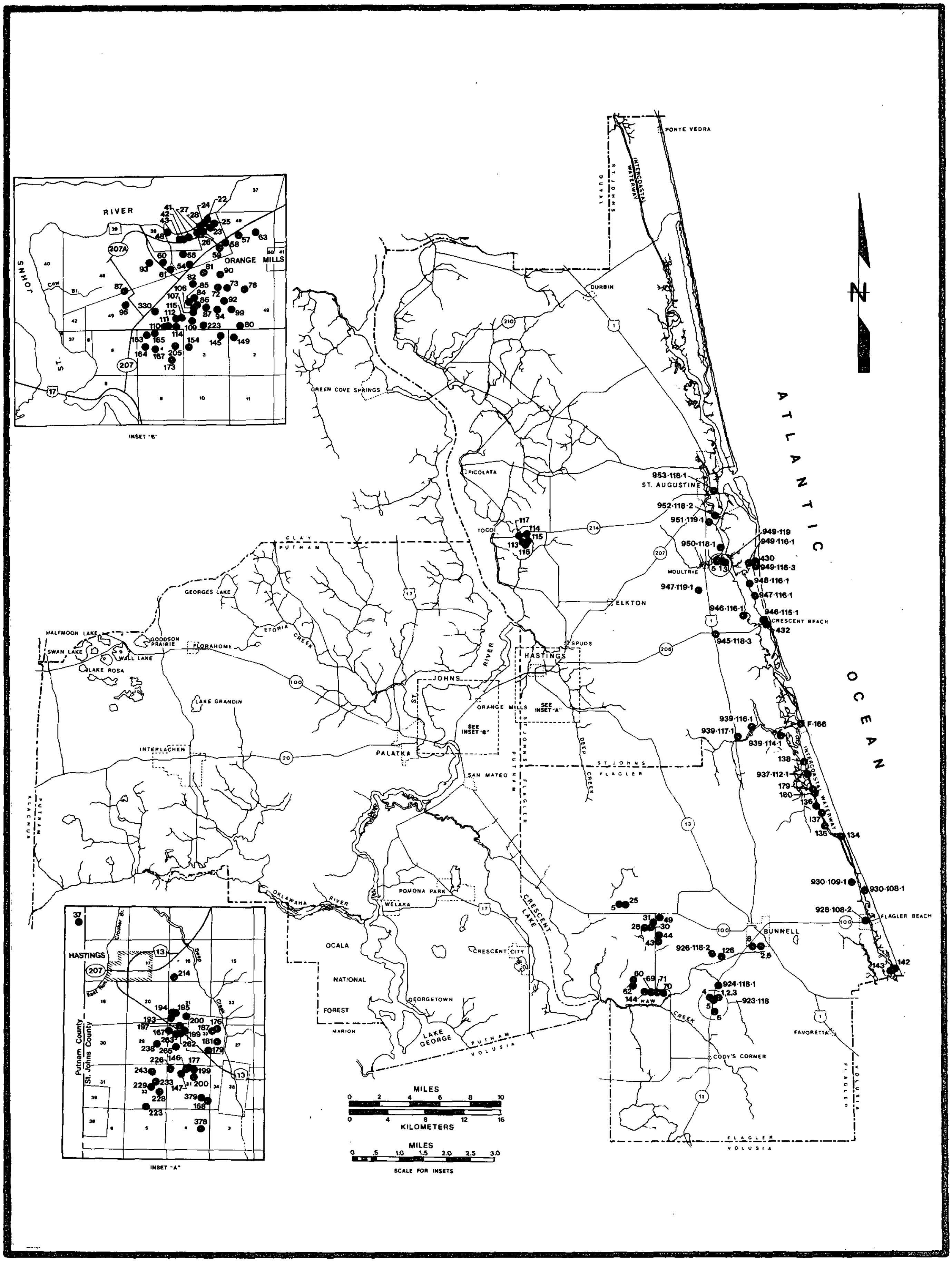


FIGURE 33. -- Map Showing Location of Wells Which Produce Water With a Chloride Concentration Greater Than 1,000 Parts Per Million

WELL SPACING

Two of the most common problems associated with large ground water withdrawals and high well density are declining water levels and deteriorating water quality. Hastings and Orange Mills have the greatest well density of the four agricultural areas within the three counties. Irrigation wells in these areas, in some instances, have been spaced as close as 10 feet apart. These areas also experience the highest levels of salt contamination during the growing season.

The highest levels of chloride concentration (Cl^-) are found near the center of the cones of depression in each agricultural area. As discussed earlier in the report, chloride concentration is related to the artesian water level (potentiometric surface) at a specific time. A high density of pumping wells result in overlapping cones of depression, and consequently, the development of multiple well interference involving the entire agricultural area. From this process, one general cone of depression is then formed. For example, if one well within a 1,000 feet circular area is pumping at 300 gpm for one day, the effective drawdown (lowering of water level) at the 1,000 feet limit would be approximately one foot (Figure 34). When other wells are pumping simultaneously within that same 1,000 feet area, the drawdown produced is the sum of all interfering cones at any one point. This situation is compounded as the number of interfering cones of depression increases.

Excessive pumpage by many interfering wells is the cause of extremely low water levels in the areas of Orange Mills, Hastings, Elkton, and Bunnell. Although aquifer water levels have the ability to recover the approximate level which existed during the non-growing season, full recovery will not occur until pumpage has decreased significantly.

Withdrawal of available ground water by all users not only causes declining water levels, but is also responsible for the noticeable reduction of pump

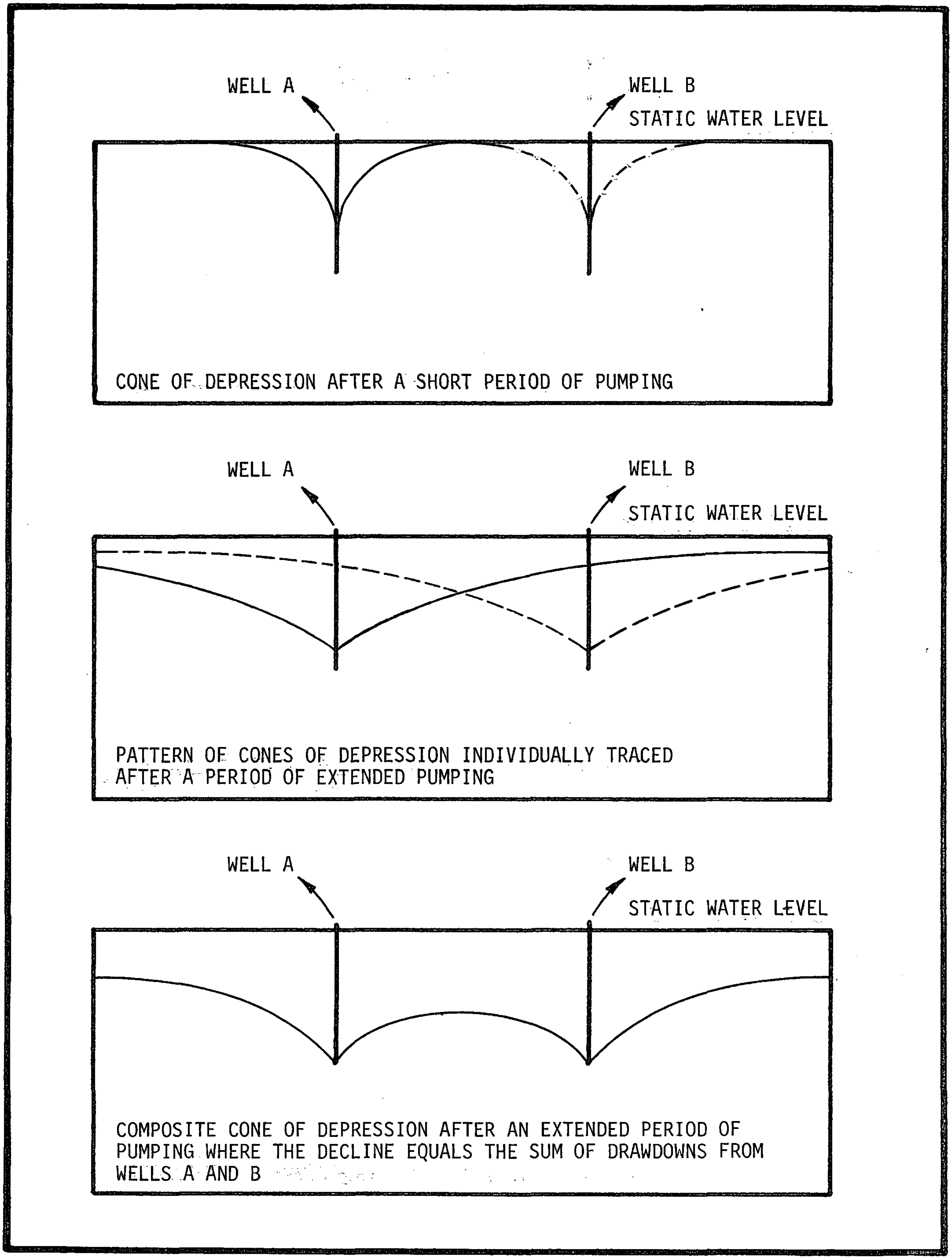


FIGURE 34. -- Development of Composite Cones of Depression by Simultaneous Pumping Wells

discharge throughout the growing season. Since the Tri-County area is an established agricultural region, the problems associated with high density and well spacing are inherent.

SALT WATER CONING

The study of salt water coning is relatively new, although it was first studied analytically by Muskat and Wyckoff (1935) in oil well production. Since 1964, several mathematical relationships have been derived concerning salt water coning in coastal aquifers. The main purpose behind the analytical and research studies was to evolve engineering design criteria for the pumping of fresh water zones overlying saline zones in a continuous aquifer. Variables which affect rate and extent of the coning process are (1) aquifer characteristics, (2) well construction and spacing, and (3) rates of ground water withdrawal.

From the geophysical investigation of this study, the fresh water/salt water interface is considered as being located at the boundary between the Ocala Formation and the Avon Park Limestone. Figure 35 shows schematically the upconing process as related to the hydrogeologic conditions in the Tri-County area. The fresh water/salt water interface is not a sharp line, but an area of dispersion or mixing. When the interface reaches a critical level within the fresh water aquifer caused by the lowering of the fresh water artesian levels, the irrigation well will withdraw directly from the contaminated water.

From investigations published by Bear and Dagan (1966a, 1966b, 1968), the rise of the fresh water/salt water interface (Z), divided by the distance at which the interface lies below the bottom of the well (d) must be less than or equal to .25 to operate without causing excessive salt contamination (Figure 36). In maintaining the ratio of $Z/d = 1/4$, the assumption is made that a dynamic equilibrium is established. The designated Z value will vary by area depending

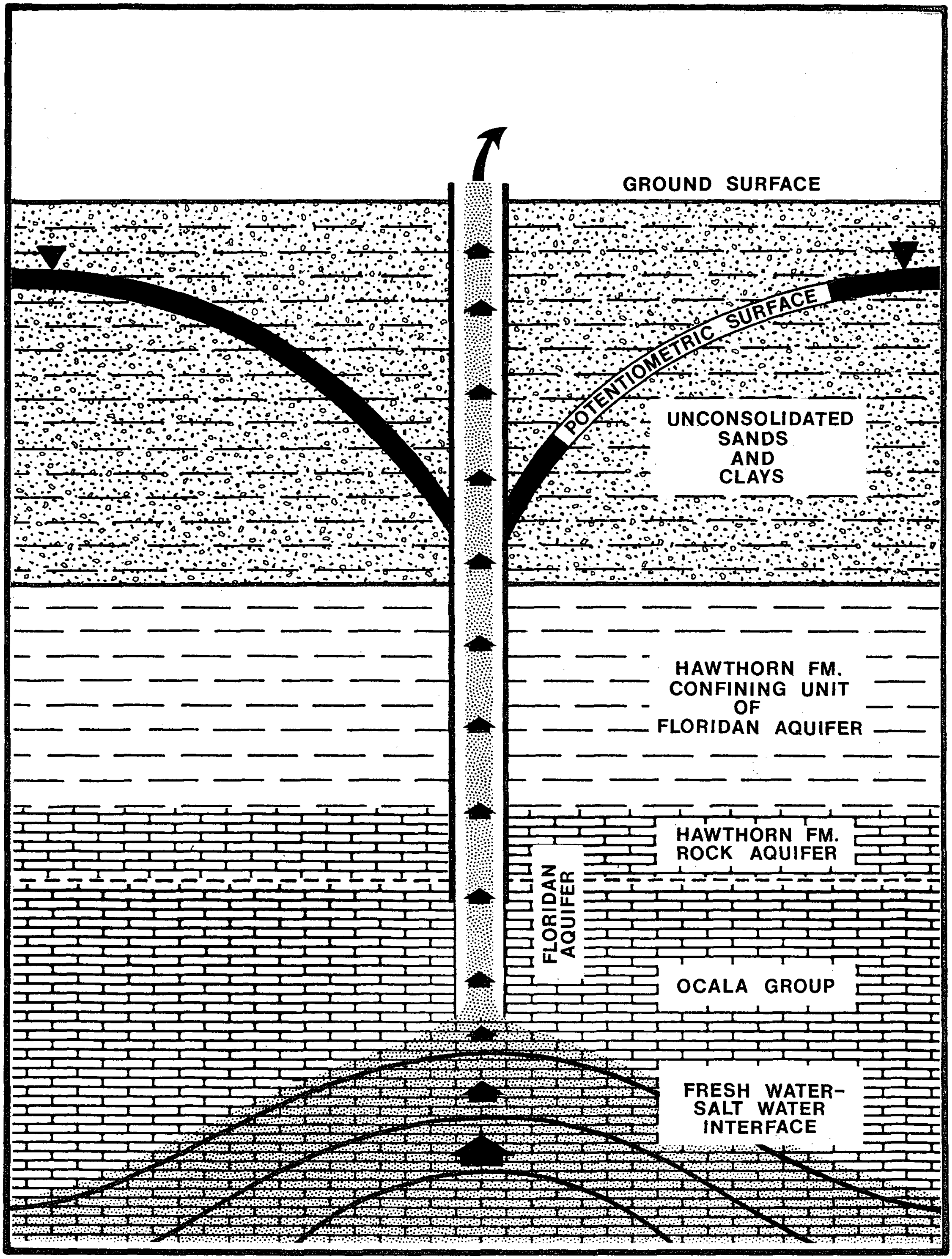


FIGURE 35. -- Schematic Diagram of Salt Water Coning as Related to the Tri-County Area

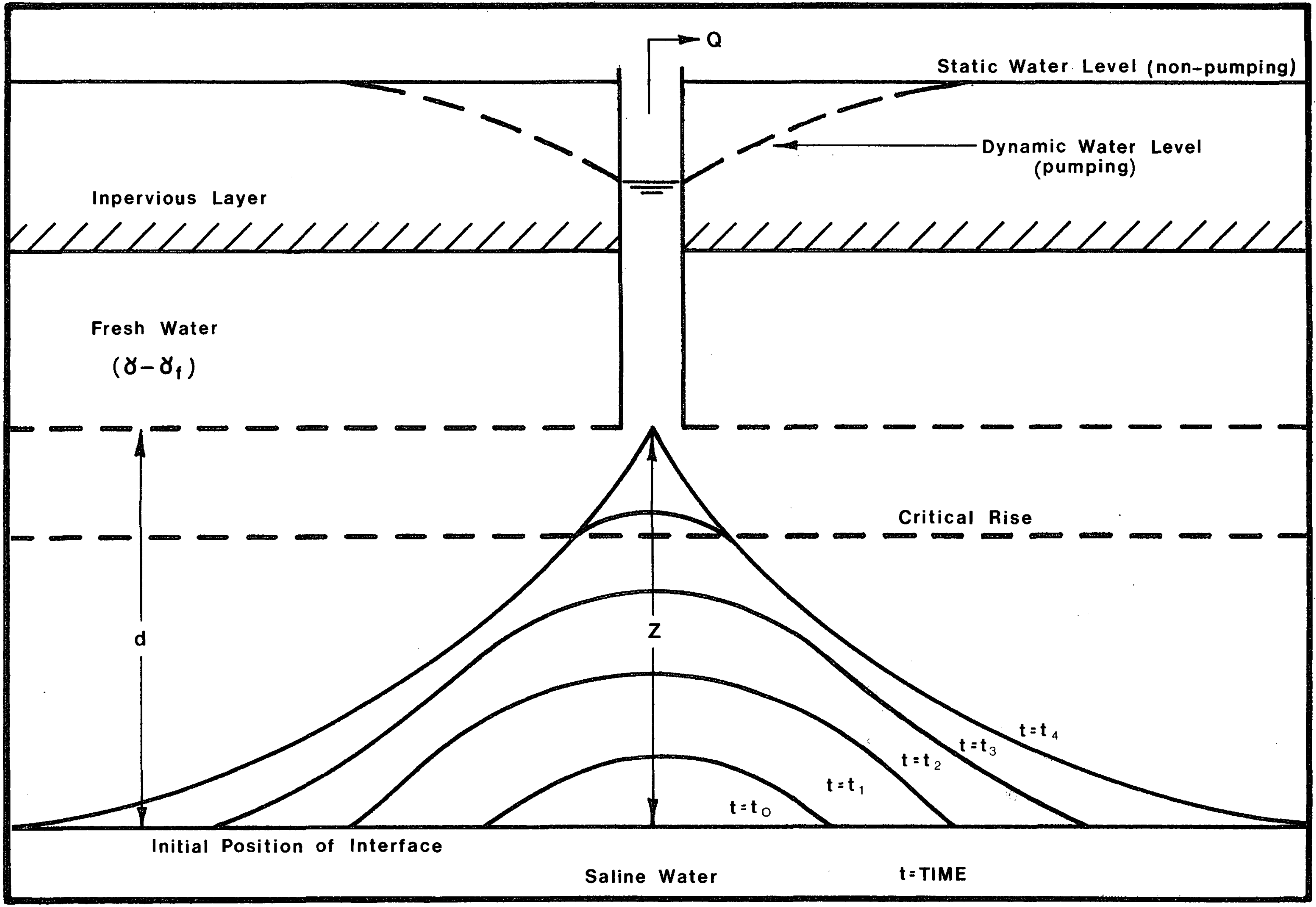


FIGURE 36. -- Upconing of an Abrupt Interface Below a Pumping Well (After Muskat, 1946 and Bear and Dagan, 1964 and 1968)

on the thickness of the fresh water aquifer. In the Tri-County area, the average maximum allowable rise of the interface is approximately 50 feet above the initial position which, in this study, is considered the top of the Avon Park limestone. As previously mentioned, aquifer penetration and pump discharge greatly influence the rate of upconing. The maximum pumping rate that can be maintained without causing the interface to rise above a critical level also depends upon the amount of fresh water aquifer penetrated by the well. In research done by R. L. Chandler and D. B. McWhorter (1975), optimum well penetration for an isotropic aquifer is nearly 30 percent of thickness and increases to more than 50 percent when vertical permeability is less than 5 percent of the horizontal permeability. Taking into consideration the variation in the hydrogeology of the study area, the theoretical maximum rate can be calculated by the following formula (Bear and Dagan, 1968):

$$Q_{max} \leq 2\pi \, d \, Z_{max} \, (\alpha/\alpha_f) \, K_x$$

where:

Q_{max} = Maximum discharge of the well

d = Initial distance between bottom of well and the center of the interface

Z_{max} = Maximum allowed rise of the interface

α/α_f = Density ratio between saline and fresh water

K_x = Horizontal permeability of the aquifer

Assuming that the aquifer is homogeneous (Bentley, 1977) and Z/d_{max} is held to 0.25, a maximum discharge rate is calculated to be 150 gallons per minute in areas where the thickness of the Ocala Group is less than 200 feet. In areas where the thickness of the Ocala Group exceeds 200 feet, discharge rates of up to 350 gallons per minute may be obtained. Figure 37 shows the recommended maximum pumping rates based on the thickness of the fresh water aquifer for the agricultural areas of Putnam, Flagler, and St. Johns counties.

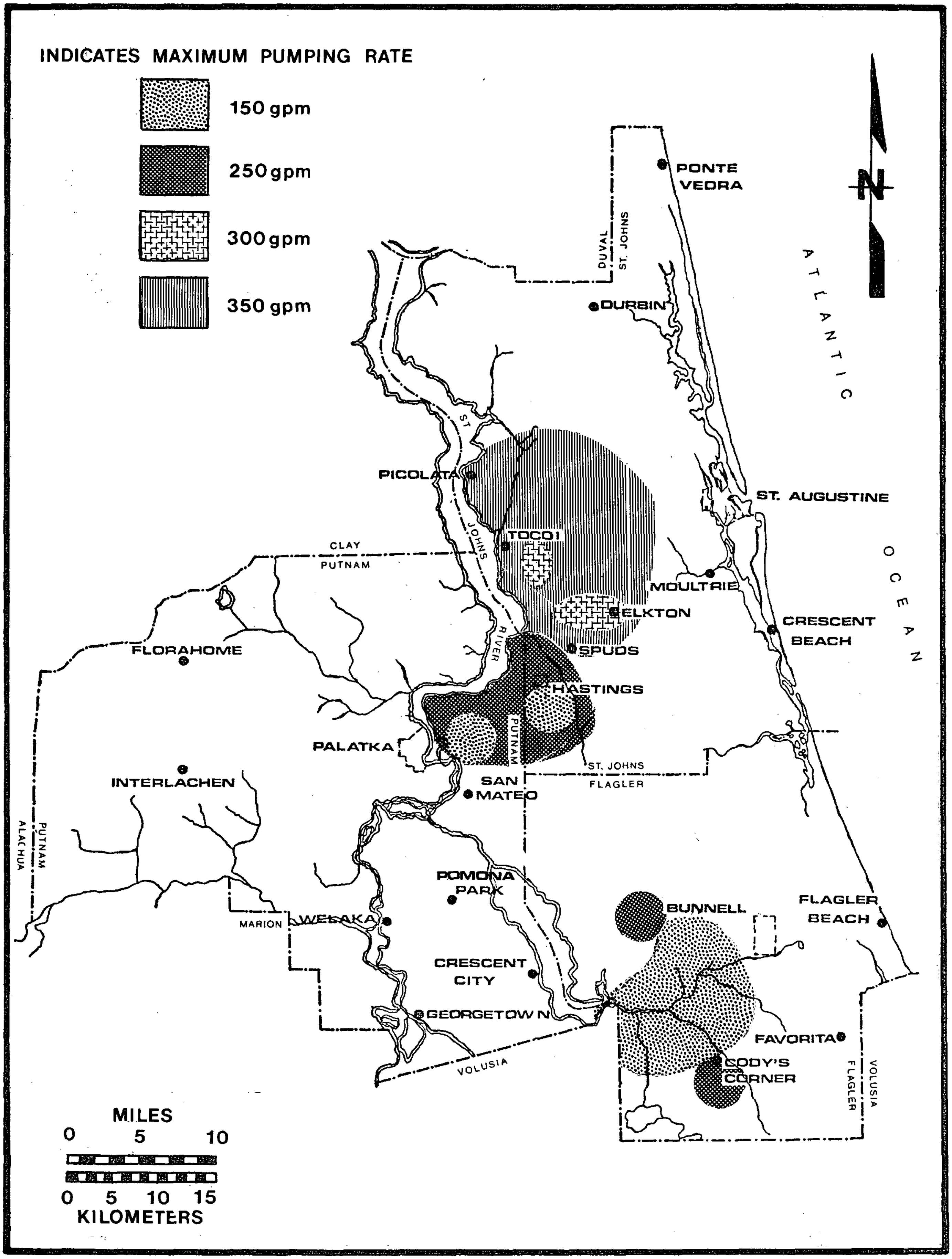


FIGURE 37. -- Map Showing the Recommended Pumping Rates for the Agricultural Areas of Putnam, Flagler, and St. Johns Counties

SUMMARY

The northeastern Florida counties of St. Johns, Putnam, and Flagler depend considerably on an agrarian economy. The Tri-County area is one of the largest producers of cabbage and potatoes in the southeastern United States. The topography is generally flat with elevations that range from 5 to 42 feet above mean sea level, and the climate is humid sub-tropical with approximately 53 inches of rainfall during the year.

From land surface to more than 200 feet in depth at some localities, the geology of this area consists of sand and clay mixed with thin beds of limestone and phosphate. Below this material is a thick section of limestone and dolomite ranging widely in purity and hardness. Typically, the upper 50 feet of the limestone (Ocala Group) appears to be the most porous, and approximately one-quarter of the wells logged located flow zones which produced water from this section. Flow zones in the remaining wells do not correlate from well to well. In deep wells just within the area of chloride contamination, water quality deteriorates as depth into the limestone increases. In the wells centrally located in the intensive agricultural areas, water quality is uniformly poor throughout the entire borehole.

Recharge to the Floridan aquifer for Putnam and St. Johns counties occurs within the "Northeast Florida Potentiometric High" area. In southern Flagler County, the "Crescent City Potentiometric High" and the "Volusia County Potentiometric High" areas are probable sources for the irrigation water derived from the Floridan aquifer. During the periods of intense pumping, local cones of depression are formed in the areas of Orange Mills, Hastings, Elkton, and Bunnell. Recharge in the form of leakage from over and underlying formations of the producing zone supply small quantities of water. The amount of water supplied by leakage is not enough to stabilize the local cones of depression.

In general, the areas and amounts of salt water contamination have increased from 1956 to 1975. Cones of depression defined by the 10-feet potentiometric contour line in Hastings, Orange Mills, and Bunnell, and the 20-feet potentiometric line in Elkton were observed only during the growing season of September through May. In the Bunnell area, artesian water levels less than 10 feet msl were continually present in the Haw Creek Basin during the entire year partly due to natural discharges along Haw Creek.

In the analysis of short term seasonal fluctuations of chloride concentrations and potentiometric levels, there exists a general inverse relationship. The lowest artesian water levels and the highest chloride concentration appeared in the central areas of the cones of depression in all three counties during the month of March. Likewise, water levels and water quality showed the greatest change in the four various cones of depression between the months of March and September. Statistical analysis of all water level and chloride data allowed predictions of chloride concentration relative to water levels. The remaining regression equations for the various cases tested are useful only for obtaining rough estimates of chloride concentrations. From the probability distribution of chloride data collected during the study period, 50 percent of all wells in the Tri-County area will produce water of chloride concentration less than or equal to 210 parts per million during any month of the year, and 10 percent of all irrigation wells, approximately 120, will produce water in excess of 778 parts per million in chloride concentration.

Statistically, the average electrical consumption rate for open discharging centrifugal pumps within the study area is 0.238 KWH per 1,000 gallons of water pumped. By simply dividing this number into electrical usage, an agriculturalist may keep records of his monthly estimated ground water withdrawals. Ground water withdrawals calculated by the electrical consumption method were approximately 50 percent lower than both the historical and most recent 1975 water use inventories conducted by the U. S. Geological Survey. Cumulatively, withdrawals in the project area were at their highest during the month of March 1975 at a rate of 36 mgd. The average annual withdrawal rate ranged from a low of 1.4 mgd for the Orange Mills area to a high of 4.9 mgd in the Hastings area. A flow-net analysis was used to confirm the validity of ground water withdrawals derived from the electrical consumption method.

Inherent problems of well construction and spacing which exist in the intensive agricultural areas are compounded by the overdraft of water used for irrigation. The direct result of those factors lead to the coning of saline water beneath pumping wells. Pumping rates calculated from various theoretical formulas which might stabilize the coning process during times of low artesian levels range from 150 gpm within the central portions of the cones of depression to as much as 350 gpm in areas where the thickness of the fresh water aquifer exceeds 200 feet. Also, those wells whose depths penetrate deeper zones of the aquifer act as conduits for contamination of the fresh upper zones. According to the statistical distribution of irrigation wells sampled during the study period, it is probable that there are in excess of 120 wells which could benefit by rehabilatative construction procedures.

RECOMMENDATIONS

This investigation was designed for two important purposes: (1) the collection of current hydrologic data and (2) utilization of that data to provide the necessary information for the evaluation and management of the resource. The recommendations listed below are based on the information presented in the text and from field observations and frequent discussions with agriculturalists during the three year study period.

The format used in presenting these recommendations points out that solutions to water resource oriented problems are multifaceted and involve several different levels of interaction. Proper management of water resources should involve the interests and efforts of everyone. Only by local support and cooperation with the Water Management District can solutions to resource problems be realized.

1. <u>The Agriculturalist</u>

    a. Practice water conservation through efficient utilization of his irrigation system.

    b. Participate in the PVC piping system program offered by the ASCS.

    c. Minimize the discharge of "tailwater" by: (1) utilizing weirs in the lateral ditches to temporarily store water for seepage and facilitate a quicker spread of water between those lateral ditches and (2) maintain higher water levels in the fields by the proper placement of adjustable weirs to hold back larger amounts of runoff which normally discharge to the larger county drainage ditches.

    d. Keep accurate records of water use for each crop during the growing season. The reason for this is to apply the adequate amount of water economically and without waste.

e. Back plug existing deep wells whose chloride concentrations exceed 1,000 ppm. The maximum allowable penetration of the aquifer in order to avoid problems of salt contamination will be approximately 30 percent of the entire thickness of that aquifer or 135 feet to as much as 200 feet into the limestone in some areas.

f. Construction of all new wells should also adhere to the 30 percent allowable penetration.

g. Construction of new wells with casing larger than six inches should utilize smaller discharge capacity pumps. Smaller capacity pumps discharging over longer periods of time have a lesser effect on water levels than a large discharge for short duration irrigation.

h. Regarding well spacing, new wells should be located no closer to each other than two times the thickness of the aquifer in that area or no closer than 250 feet.

2. <u>Other Agencies (IFAS, ASCS, SCS)</u>

a. Continue to promote and encourage efficient irrigation practices and water conservation.

b. Develop systems to return excess water from the large quantities of runoff leaving individual systems.

c. Have more local programs and seminars to relay new developments and techniques in irrigation to the agriculturalist.

3. <u>The District</u>

a. Continue support of the ASCS-SCS well plugging program.

b. Mass sample and reinventory those areas which chloride concentration exceeds 1,000 ppm during low potentiometric levels, geophysically log those contaminated wells, and make recommendations for plugging wells which are contaminated.

c. Conduct detailed pump test to further evaluate the process of salt water coning in the intensive agricultural areas.

d. Develop a computer simulation model of the Floridan aquifer in this area to predict local and regional trends of artesian water levels and water qualities.

e. Exercise the District's authority in the regulation of abandoned and free-flowing wells.

f. Continue a long term monitoring program of selected irrigation wells to maintain a data base for prediction of future trends and evaluation of corrective measures.

REFERENCES

Anderson, K. E., 1973, Water Well Handbook: Missouri Water Well and Pump Contractors Assoc., Inc., 281 p.

Bear, J. and Dagan, G., 1964, The transition zone between fresh and salt waters in coastal aquifers: Technion Research.

__________, 1966a, Increasing the yield of coastal collector by means of special operation techniques: Progress Report No. 4, Technion Research.

__________, 1966b, The transition zone at the rising interface below the collector: Progress Report No. 5, Technion Research.

__________, 1968, Solving the problem of local interface upconing in a coastal aquifer by the method of small perturbations: Journal of Hydraulic Research, Vol. 6, No. 1, p. 16-44.

Bentley, C., 1977, Aquifer test analyses of the Floridan aquifer in Flagler, Putnam, and St. Johns counties, Florida: U. S. Geol. Survey Water Resources Investigation Series, WRI 77-36, 50 p.

Bermes, B. J., Leve, G. W., and Tarver, G. R., 1963, Geology and ground water resources of Flagler, Putnam, and St. Johns counties, Florida: Fla. Geol. Survey Rept. Inv. No. 32, 97 p.

__________, Ground water records of Flagler, Putnam, and St. Johns counties, Florida: Fla. Geol. Survey Inf. Circ. No. 37, 89 p.

Chandler, R. L. and McWhorter, D. B., 1975, Upconing of the salt water/fresh water interface beneath a pumping well: Ground Water, Vol. 13, No. 4, p. 354-359, July-August.

Chen, Chih Shan, 1965, The regional lithostratigraphic analysis of Paleocene and Eocene rocks of Florida: Fla. Bur. of Geol. Bulletin 45, 105 p.

Clark, W. E., Musgrove, R. H., Menke, C. G., and Cagle, Jr., J. W., 1964, Water resources of Alachua, Bradford, Clay, and Union counties, Florida: Fla. Bur. of Geol. Rept. Inv. No. 35, 170 p.

Cooke, C. W., 1939, Scenery of Florida as interpreted by a geologist: Fla. Bur. of Geol. Bulletin 17, 120 p.

Davis, J. C., 1973, Statistics and data analysis in geology: John Wiley and Sons, Inc., New York, 550 p.

Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., 1962, Theory of aquifer tests: U. S. Geol. Survey Water Supply Paper 1536-E, 174 p.

Florida Water Resources Study Commission, 1956, Florida's water resources, a study of the physical, administrative and legal aspects of water problems and water management, agricultural, industrial, municipal, and recreational: p. 1-94.

Jacuzzi, Engineering information for pumps and water systems: p. 1-24.

Johnson, R. A., 1979, Geology of the Oklawaha Basin: St. Johns River Water Management District Technical Report No. 1, 24 p.

Leach, S. D., 1978, Source, use, and disposition of water in Florida, 1975: U. S. Geol. Survey Water Resources Investigation 78-17.

Muskat, M. and Wyckoff, R. D., 1935, A. I. M. E., 114, Pet. Dev. Techn. p. 144.

Phelps, G. G., 1978, Methods of estimating recharge to the Floridan aquifer in Northeast Florida: U. S. Geol. Survey Water Resources Investigation 77-109, 19 p.

Plappert, J., Johnson, R., Helpling, C., 1975, Report on geophysical logging of selected wells in eastern Putnam and St. Johns counties, Department of Environmental Regulation, Tallahassee, Florida.

Pride, R. W., 1970, Estimated water use in Florida, 1965: U. S. Geol. Survey Map Series No. 36.

___________, 1973, Estimated use of water in Florida, 1970: U. S. Geol. Survey Information Circular No. 83, p. 3-15.

Puri, H. S., 1957, Stratigraphy and zonation of the Ocala Group: Fla. Bur. of Geol. Bulletin No. 38, 248 p.

Rao, D. V., 1978, A criterion for selecting the probability density function of best fit for hydrologic data: Ph.D. Thesis, Georgia Institute of Technology, Atlanta, Georgia.

Rohlf, J. F. and Sokal, R. R., 1969, Statistical tables: W. H. Freeman and Company, San Francisco, 253 p.

Soil Conservation Service, 1962, Irrigation pumping plants: SCS National Engineering Handbook, Chapter 8, Section 15, p. 1-70.

White, W. A., 1970, Geomorphology of the Florida peninsula: Fla. Bur. of Geol. Bulletin No. 51, 164 p.