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DARE COUNTY WATER DEPARTMENT
HATTERAS WATER SYSTEM
REVERSE OSMOSIS WELLFIELD STUDY
DARE COUNTY, NORTH CAROLINA

Prepared for:

The Dare County Water Department
600 Mustian Street
Kill Devil Hills, NC 27948

March 1998
(Revised October 1998)

By:

Missimer International, Inc.
8140 College Parkway, Suite 202
Fort Myers, FL 33919

Project No. FH7-574

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FH7574RV.RP1

MISSIMER INTERNATIONAL INC.

October 14, 1998

Mr. Bob Oreskovich
Dare County Water Department
600 Mustian Street
Kill Devil Hills, NC 27948

Re: Report on the Hatteras Water System Reverse Osmosis Wellfield Study

Dear Bob:

Enclosed, please find three copies of the report entitled "Dare County Water Department, Hatteras Water System Reverse Osmosis Wellfield Study." The report includes minor revisions to the draft that was sent to you in April and documents the methods and procedures used during the investigation to assess the feasibility of developing a source of raw water for reverse osmosis treatment on Hatteras Island. Results of the investigation indicate that the Mid-Yorktown aquifer is capable of yielding 4.2 MGD of brackish water on a sustained basis. A proposed wellfield alignment and construction details for the production wells are presented herein. In addition, estimated changes in raw water quality due to pumpage from the wellfield are projected for a 30 year period.

We appreciate the opportunity to continue providing services to Dare County and look forward to working with you during development of the raw water supply wellfield.

Sincerely,

Wm. Scott Manahan, P.E.
Water Resource Engineer

W. Kirk Martin, P.G.
Vice President
Hydrology Services

WSM/WKM/lk
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EXECUTIVE SUMMARY

A large quantity of freshwater is stored within the water-table aquifer on Hatteras Island. A shallow wellfield that taps this aquifer in the Buxton Woods area is currently used for public supply purposes on the island. Expansion of the wellfield to meet the increasing demand for water is not feasible due to the potential for adverse environmental impacts and saline water intrusion. A study of the brackish groundwater resources available beneath the island was initiated to identify a supply of water to meet projected demands.

An aquifer capable of yielding large volumes of brackish water was encountered between the depths of approximately 240 and 300 feet below land surface in the vicinity of the existing water treatment plant on the island. Water quality within the aquifer is highly variable with dissolved chloride concentrations that range from 3700 mg/l to over 10,000 mg/l in the study area. Water from this aquifer can be treated relatively economically using reverse osmosis technology. A new reverse osmosis water treatment plant is proposed for construction on the island. Permeate from the reverse osmosis plant will be blended with ion-exchange treated water from the shallow wellfield to produce a high quality potable water which meets all federal primary and secondary drinking water standards.

The purposes of this investigation were: to determine the quantity of brackish water available, to obtain sufficient hydrogeologic information to assure the long term viability of the resource, to develop an optimal wellfield design, and to estimate pumpage induced changes in raw water quality that might occur with time. The investigation included a review and compilation of previous test data, drilling additional test wells, aquifer performance testing, water quality sampling, and the evaluation of drawdown impacts and anticipated water quality changes for various wellfield development scenarios by using computer model simulations.

Results of the investigation indicate that the high permeability limestone unit within the upper part of the Mid-Yorktown aquifer has the capability to yield the projected 4.2 MGD of brackish raw water need on a sustained basis. Raw water obtained from this source is anticipated to have an average initial dissolved chloride concentration of 4000 to 5000 mg/l. Computer model simulations indicate that over a 30 year period, an increase in dissolved chloride concentration up to 8000 mg/l may occur in the raw water as a result of the proposed pumpage. Model results also show no adverse impacts to the surficial aquifer system or the surface environment.

1.0 CONCLUSIONS AND RECOMMENDATIONS

A detailed study of the brackish groundwater resources available for reverse osmosis treatment beneath the Buxton Woods area of Hatteras Island has been completed. The study was conducted to obtain information regarding the long term raw water supply capacity of the upper part of the Mid-Yorktown aquifer which was previously identified as a potential brackish water source (Missimer International, 1995). This source is capable of yielding an abundant supply of brackish feedwater for reverse osmosis treatment. The following conclusions and recommendations are presented based on the results of drilling, aquifer performance testing, data analyses, and computer modeling that were conducted as part of the investigation.

1.1 Conclusions

- Seven test wells were constructed in the vicinity of the existing Dare County water treatment facility on Hatteras Island as part of this investigation. The wells were installed to obtain additional information regarding yield characteristics and water quality conditions of the Mid-Yorktown aquifer in the study area. Three test wells were constructed in the area previously as part of a preliminary investigation to evaluate the feasibility of developing a raw water source for reverse osmosis treatment on the island. All of the test wells were completed within the Pliocene age Yorktown Formation.

- A high permeability fossiliferous limestone unit was encountered in each of the test wells between the approximate depths of 240 and 300 feet below land surface. This unit is the target production zone for the raw water supply wells proposed for construction on the island. A sequence of low permeability sandy clay units with a thickness of over 100 feet provides confinement between the Mid-Yorktown aquifer and the overlying water-table aquifer. Permeability of the limestone within the Mid-Yorktown aquifer decreases with depth and provides a limited degree of confinement from underlying units.

- Aquifer performance testing was conducted in the area proposed for wellfield development by pumping a test/production well that taps the upper part of the Mid-Yorktown aquifer. Water levels in selected test wells were monitored prior to, during, and after pumping the test/production well. The drawdown and recovery data collected were analyzed to calculate pertinent aquifer hydraulic coefficients required for computer modeling purposes. The test results indicate that the proposed production aquifer is highly transmissive and capable of yielding large volumes of water. The following values were used for the upper part of the Mid-Yorktown aquifer in developing the computer models.

  Transmissivity = 240,000 gpd/ft

  Storage Coefficient = 5.0×10^{-5}

  Upper Leakance = 1.3×10^{-4} day^{-1}

  Lower Leakance = 2.5×10^{-2} day^{-1}

- Water quality in the proposed production zone and deeper intervals was evaluated by sampling the test wells constructed for the investigation. Water quality is highly variable both laterally and with depth. Dissolved chloride concentrations of samples obtained from the wells ranged from 3700 mg/l to 10,500 mg/l in the production zone interval and up to 10,800 mg/l in underlying units. A general trend of increasing dissolved chloride concentration from west to east and with depth was noted in the samples.

- Hydraulic and solute transport computer models were constructed to estimate water level and water quality changes that may occur due to the proposed pumpage. The hydraulic model results indicate that an aquifer drawdown of approximately 5 feet would occur near the center of the proposed wellfield alignment due to long term pumpage at a total production rate of 4.2 MGD. The solute transport model results indicate that dissolved chloride concentrations would increase from an initial average value of approximately 4500 mg/l to approximately 7500 mg/l during the 30 year simulation period. The solute transport model considered seasonal variations in pumping rates and utilized a peak pumping rate of 4.2 MGD during the final 10 years of the simulation. Model estimates of peak drawdown in the surficial aquifer were less than 0.1 feet under no recharge conditions.

- A preferred wellfield alignment was selected based on several factors including: hydraulic and solute transport modeling results, locations of existing and proposed infrastructure, proposed water treatment and reverse osmosis brine disposal considerations, site logistics, and the overall economics of the water supply project. A sustained yield of 4.2 MGD of raw water suitable for reverse osmosis treatment can be obtained from a wellfield consisting of four wells tapping the upper part of the Mid-Yorktown aquifer on Hatteras Island. Pumpage in excess of this amount to meet possible future increases in demand may be feasible by expanding the wellfield in a westerly direction.

1.2 Recommendations

- Three production wells should be completed within the upper part of the Mid-Yorktown aquifer and used with the existing test/production well R.O. TW-3 to supply raw water to the proposed reverse osmosis plant at a rate of up to 4.2 MGD. The wells should be constructed in an alignment along Highway 12 with a spacing of approximately 2000 feet between wells. Proposed production well locations are shown on enclosed figures.

- The proposed production wells should be constructed with 12-inch diameter PVC casings extending to a depth of approximately 250 feet below land surface. A hydrogeologist should supervise construction of the wells and recommend final cased and total depths at each site based on lithologic analysis of formation samples obtained during drilling and testing. Open hole sections of the wells should be constructed to a depth not to exceed 300 feet below land surface utilizing the reverse air drilling technique. No drilling fluid, other than clean water, should be used in the production zone. The new production wells and existing test/production well R.O. TW-3 should be thoroughly developed with compressed air to remove all drill cuttings and sediment from the open boreholes.

- Step-drawdown pump tests should be conducted on the new production wells. Specific capacity values calculated based on the test results can be used to assess individual well yields and confirm the proposed pump setting depths and withdrawal rates. All of the production wells should be disinfected following development and pump testing. Submersible pumps equipped with variable frequency drive electric motors should be installed in the wells with the intakes set at 30 to 40 feet below land surface for production purposes. Recommended withdrawal rates for the proposed wells range from 350 to 750 gpm and can be varied to meet the treatment plant demands.

- Static and pumping water levels in each of the production wells should be measured on a periodic basis. In addition, water quality samples should be obtained from each of the production wells and analyzed for salinity indicator parameters such as dissolved chloride concentration, total dissolved solids, or specific conductance. The water level and water quality data will enable an evaluation of wellfield performance and help to identify potential problems. Water level and water quality data should also be collected from the reverse osmosis test wells on a periodic basis. Water quality data from the deeper zone monitor wells may provide an early indication of water quality changes to be expected in the production zone. Monitoring of the test wells should be initiated soon to obtain background data before the wellfield is put into operation.

2.0 INTRODUCTION

2.1 Project History

Potable water supply for the communities of Avon, Buxton, Frisco and Hatteras Village on Hatteras Island is obtained from a shallow wellfield that taps the water-table aquifer. Increased pumpage from this source to meet growing demands is not feasible due to concerns for environmental impacts and the potential for saltwater intrusion into the wellfield. Missimer International, Inc. (MI) was authorized by the Cape Hatteras Water Association (CHWA) in March 1995 to conduct test drilling in order to make a preliminary evaluation of the potential for developing a brackish raw water supply for reverse osmosis treatment on the island. Results of the initial test drilling project indicated that large scale brackish water supply development was feasible. A detailed hydrogeologic investigation including additional test well construction, aquifer performance testing, water quality sampling, data analyses, and computer modeling was recommended to further evaluate the proposed brackish water source prior to full scale design and development of the resource. The Dare County Water Production Department acquired the assets of the CHWA and assumed operation of its facilities during July of 1997 and authorized MI to conduct the proposed test program. This report has been prepared to document the methods and procedures used during the investigation and the results obtained. A more complete discussion of the project work scope is presented below. A map showing the general location of the project site is provided as Figure 2-1.

2.2 Work Scope

The scope of the project included: 1) review of the data collected during the preliminary feasibility study, 2) construction of test wells in the vicinity of the proposed reverse osmosis treatment plant site and adjacent areas to assess the areal extent of the limestone aquifer, 3) collection of lithologic and water quality data during well construction and testing, 4) aquifer performance testing to determine pertinent aquifer hydraulic characteristics, 5) development of hydraulic and solute transport computer models to evaluate wellfield development scenarios and

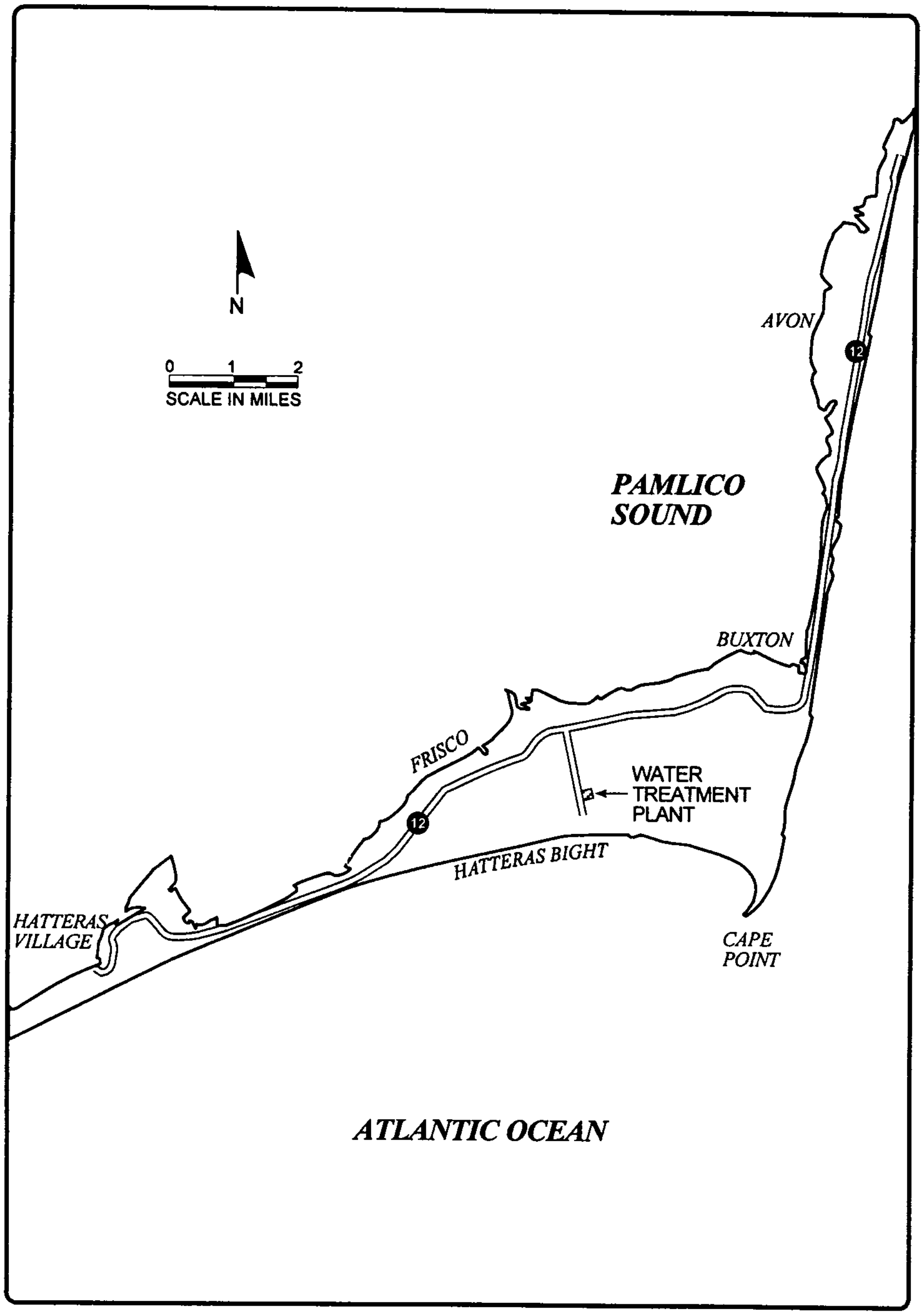

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FIGURE 2-1. MAP SHOWING THE STUDY AREA AND LOCATION OF THE WATER TREATMENT PLANT.

determine water level and water quality changes that may result due to pumpage at rates up to 4.2 MGD, 6) preparation of a report summarizing the investigation, and 7) provision of technical specifications for construction of the reverse osmosis production wells.

The drilling and testing procedures used during the investigation are presented herein along with a discussion of the hydrogeology of the study area and descriptions of how the computer models were set up. Water quality data obtained by sampling the test wells constructed for the study were used in the solute model. The MODFLOW computer code developed by the United States Geological Survey was used to construct the hydraulic flow model. Aquifer parameters utilized in the model were determined from the results of aquifer performance testing conducted near the proposed water treatment plant site. Solute transport modeling was accomplished using the MT3D computer code developed by the Environmental Protection Agency.

3.0 METHODS OF INVESTIGATION

3.1 Test Well Construction

Three test wells (R.O. TW-1 through R.O. TW-3) were constructed near the existing water treatment plant site during the spring and summer of 1995 as part of the preliminary study to assess the feasibility of brackish water supply development on the island. Seven additional test wells were constructed as part of this investigation. A Missimer International hydrogeologist supervised the drilling and collected formation samples for lithologic analyses. Lithologic logs of the sediments encountered in each test well are included in the appendices. Locations of the test wells are shown on Figure 3-1. A discussion of the procedures used during drilling of the seven additional test wells is presented below.

The mud rotary method was used to drill the test wells. Drilling began in the last week of September 1997 and was completed in December. Five of the test wells (R.O. TW-4 through R.O. TW-8) were completed within the upper part of the limestone unit within the proposed production zone. Test well R.O. TW-310 was completed just below the production zone and test well R.O. TW-410 was completed approximately 100 feet below the production zone interval. The production zone monitor wells were constructed with six-inch diameter SDR 17 PVC casings and open hole sections. The deeper zone monitor wells were nested together and completed with 2-inch diameter schedule 40 PVC casings and 10 foot screened intervals. Construction details for the test wells are summarized in Table 3-1. Schematic diagrams of the wells are provided as Figures 3-2 and 3-3. Schematic diagrams of the original three test wells are included in the appendix. All of the wells were developed with compressed air following the completion of drilling. Water samples were obtained while the wells were being developed and subsequently analyzed for dissolved chloride concentration. Results of the water quality sampling are discussed in section 3.4 of this report.

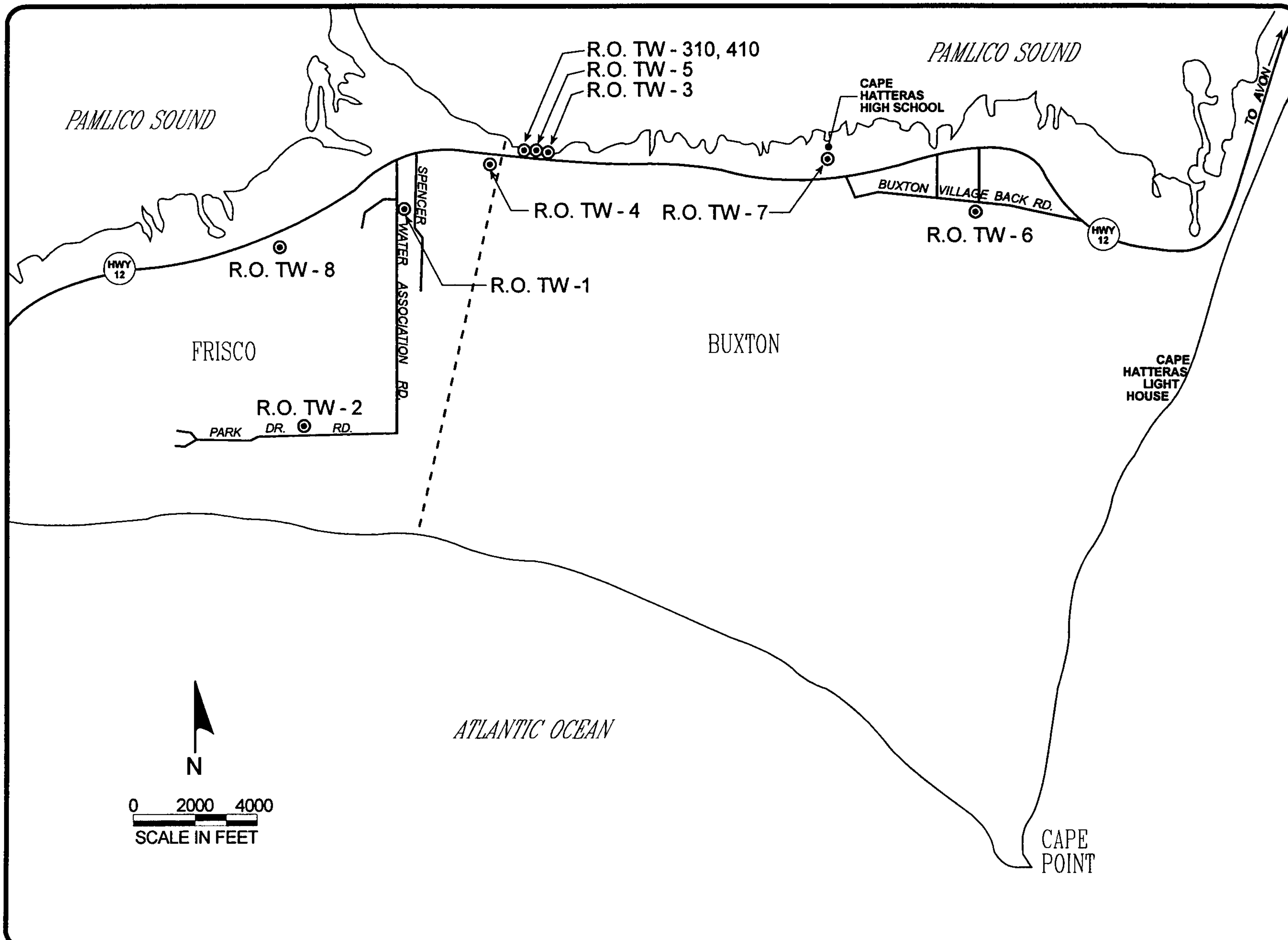

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FIGURE 3 - 1. SITE MAP SHOWING REVERSE OSMOSIS TEST WELL LOCATIONS.

TABLE 3-1. SUMMARY OF CONSTRUCTION DETAILS FOR THE DARE COUNTY HATTERAS WATER SYSTEM REVERSE OSMOSIS TEST WELLS

Well Number and Zone Tested	Casing Depth (feet below land surface)	Casing Diameter and Type
R.O. TW-1 Upper Zone (238'-275') Lower Zone (557'-588')	240 560	6-inch Sch 80 PVC 2-inch Sch 40 PVC
R.O. TW-2 Upper Zone (244'-285') Lower Zone (583'-650')	246 625	8-inch Sch 80 PVC 4-inch Sch 40 Steel
R.O. TW-3 (244'-276')	248	10-inch Sch 80 PVC
R.O. TW-4 (247'-278')	247	6-inch SDR 17 PVC
R.O. TW-5 (253'-284')	253	6-inch SDR 17 PVC
R.O. TW-6 (282'-322')	282	6-inch SDR 17 PVC
R.O. TW-7 (288'-326')	288	6-inch SDR 17 PVC
R.O. TW-8 (246'-329')	246	6-inch SDR 17 PVC
R.O. TW-310 (305'-315')	305	2-inch Sch 40 PVC
R.O. TW-410 (400'-410')	400	2-inch Sch 40 PVC

GENERAL CONSTRUCTION DETAILS
DARE COUNTY HATTERAS WATER SYSTEM
REVERSE OSMOSIS TEST WELLS

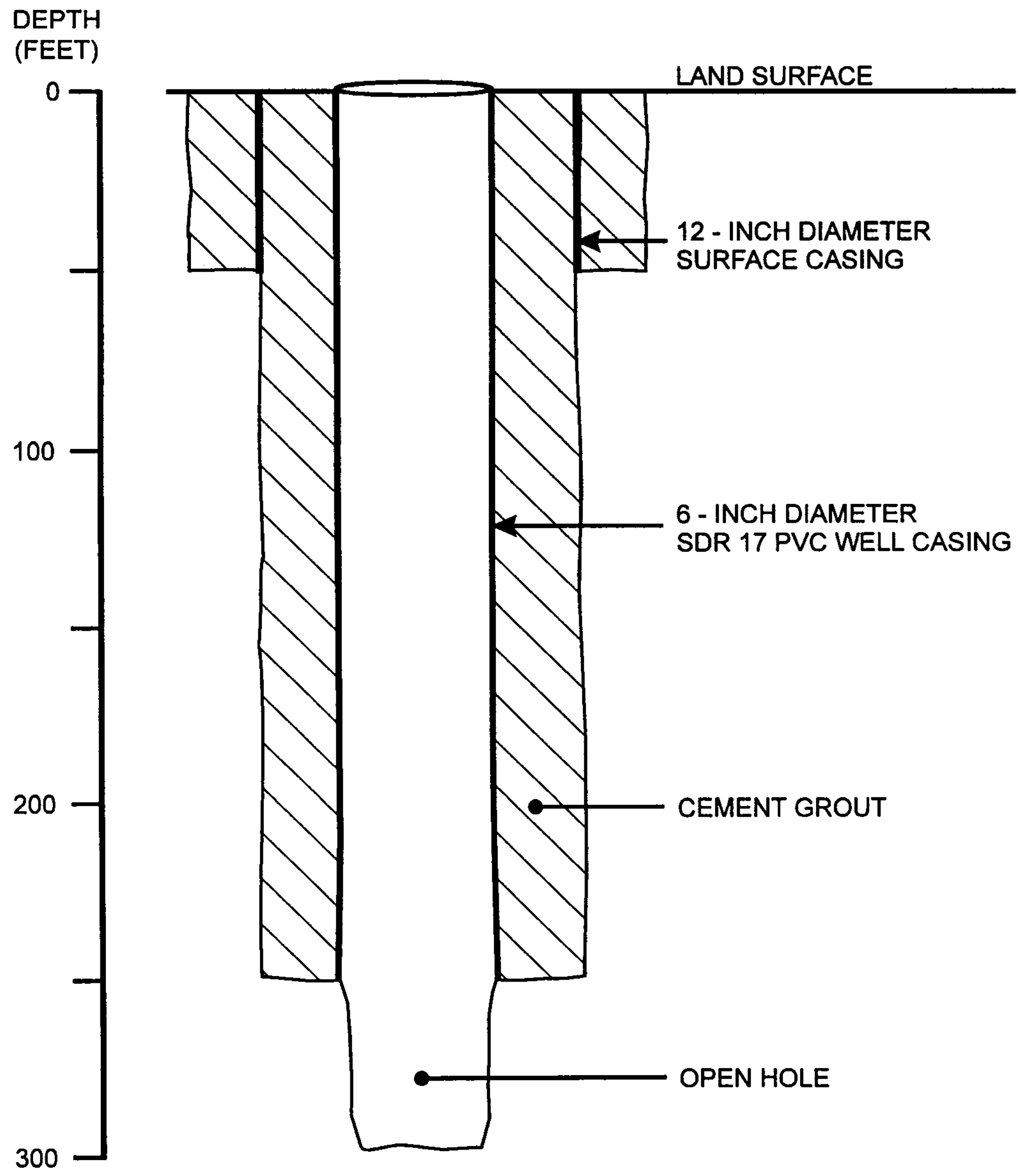

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FIGURE 3-2. SCHEMATIC DIAGRAM SHOWING GENERAL CONSTRUCTION DETAILS FOR REVERSE OSMOSIS TEST WELLS R.O. TW-4 THROUGH R.O. TW-8. CASED AND TOTAL DEPTHS OF THE WELLS VARY.

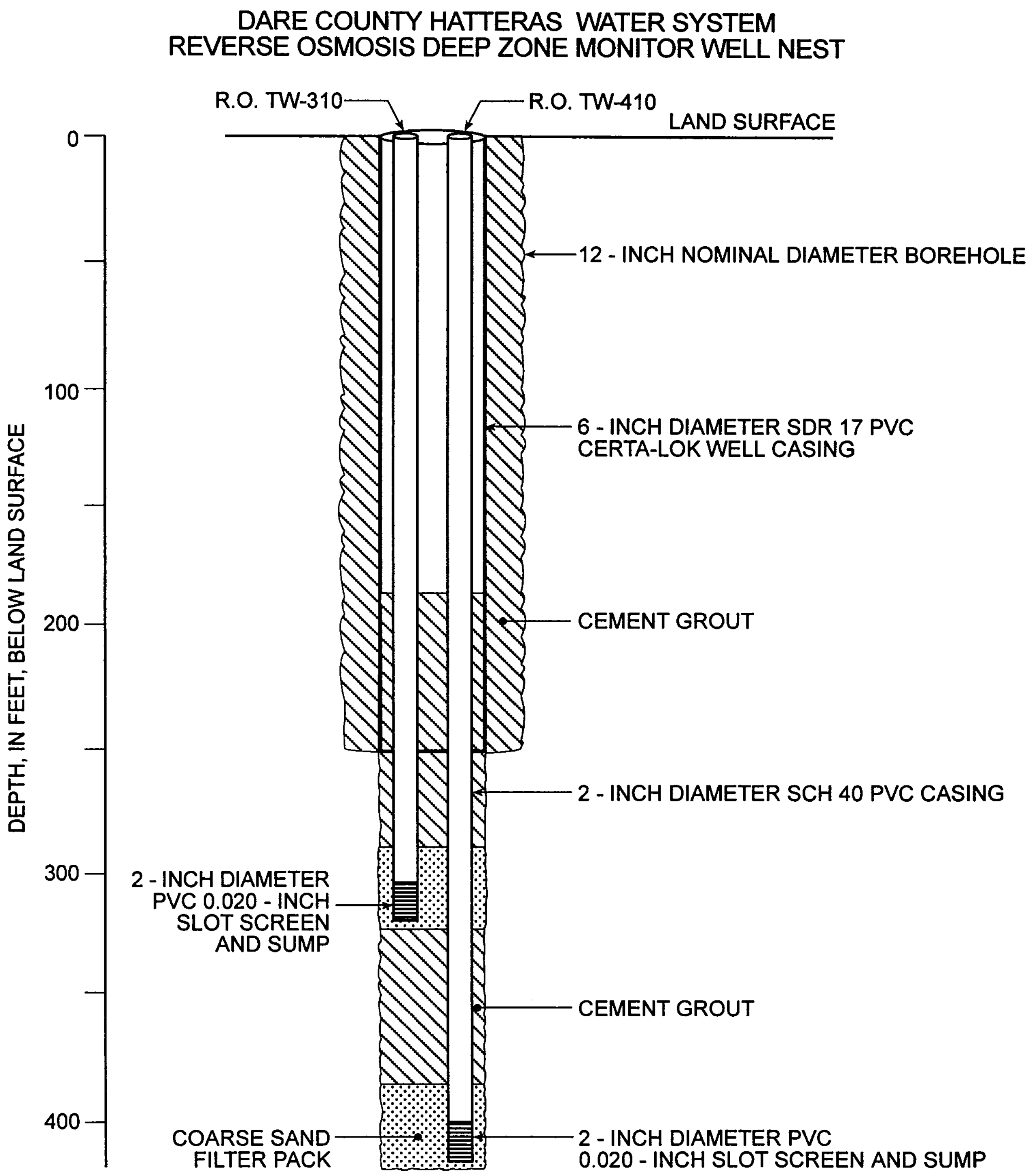

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FIGURE 3 - 3. SCHEMATIC DIAGRAM SHOWING CONSTRUCTION DETAILS FOR REVERSE OSMOSIS TEST WELLS R.O. TW-310 AND R.O. TW-410.

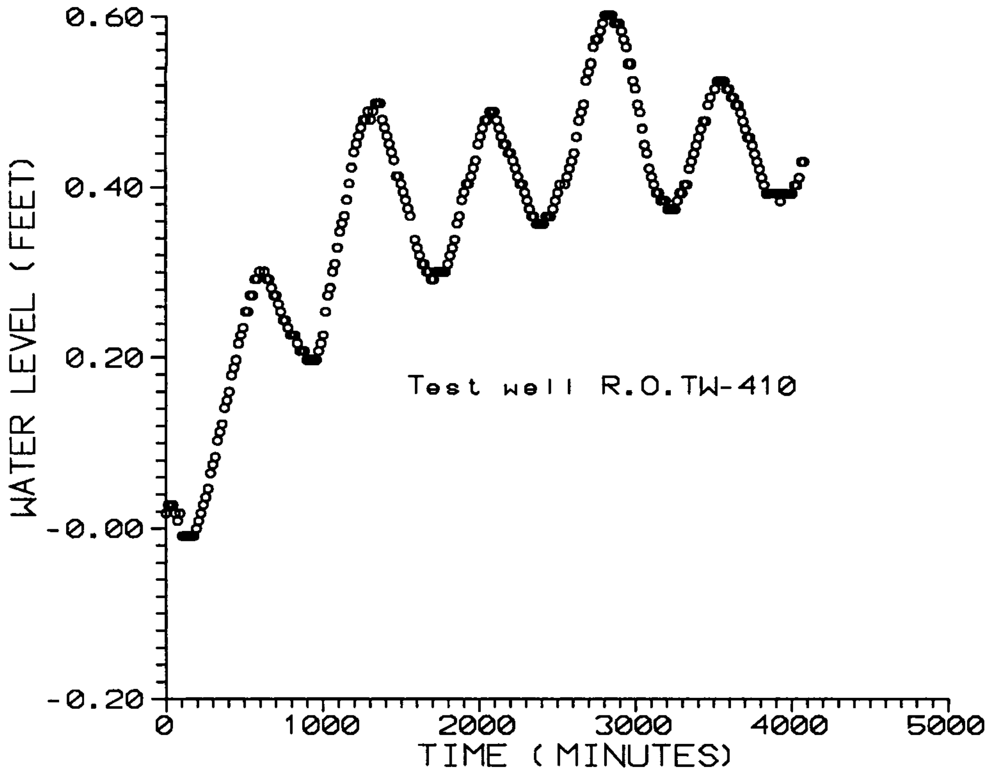
3.2 Aquifer Performance Testing

A constant rate aquifer performance test (APT) was conducted to determine aquifer hydraulic coefficients for the Mid-Yorktown aquifer in the vicinity of the proposed reverse osmosis plant. Test/production well R.O. TW-3 was pumped at a constant rate of 500 gpm while drawdown/recovery data were measured in four nearby monitor wells. Water levels in the production zone interval were measured in wells R.O. TW-4 and R.O. TW-5 at distances of 440 feet and 95 feet from the pumped well, respectively. Water levels were also measured in the deeper zone monitor well nest approximately 100 feet from the pumped well to determine the pressure effect of pumpage on underlying units. Data from the deeper zone wells were used for calibration of the computer models and provide an indication of the potential for upconing due to pumpage.

An electric submersible pump was used for the APT. The produced water was piped away from the test site and discharged into Pamlico Sound. The pumping rate was measured using a flow meter near the pump. Drawdown/recovery data were measured and recorded using pressure transducers coupled to electronic data loggers. Background data were collected in monitor wells R.O. TW-5 and R.O. TW-410 for three days prior to starting the test (Figure 3-4). The background data show that natural water level fluctuations of approximately 0.2 to 0.3 feet occur in the aquifer at intervals of approximately six hours. The period and magnitude of the water level changes suggest the fluctuations are due to tidal influences. The APT was started at 12:45PM on December 19, 1997 and allowed to run for approximately 11 days before the pump was shut down at 9:25AM on December 30, 1997. Recovery data were collected for 24 hours following the test. The aquifer test data were transferred to a computer for plotting and analyses as described in section 3.3.

3.3 Aquifer Test Data Analyses

Analysis of the data collected during the aquifer performance test was accomplished using the method developed by Cooper (1963). Logarithmic plots of drawdown vs. time were constructed



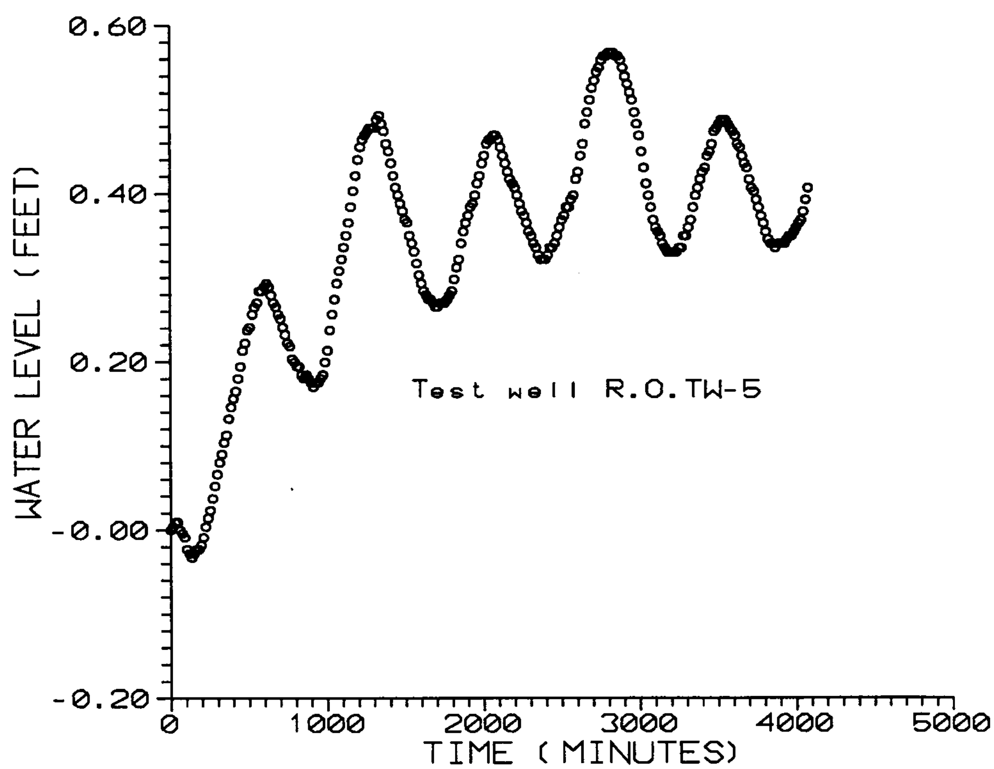


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FIGURE 3-4. Background water levels in test wells R.O.TW-5 and R.O.TW-410 prior to the APT.

using data from wells R.O. TW-5 and R.O. TW-4. The log-log graphs are included as Figures 3-5 and 3-6. The plots were compared to the appropriate type curves and match points were obtained. The data were substituted into the following equations (after Cooper 1963 with appropriate unit conversions) to obtain the aquifer hydraulic coefficients of transmissivity, storage, and leakance.

$$T = \frac{Q\ L\ (u,v)}{4\ \pi\ s} \qquad (1)$$

$$S = \frac{4\ T\ t}{r^2\ (1/u)} \qquad (2)$$

$$L = \frac{4T\ (v)^2}{r^2} \qquad (3)$$

where,

T =	transmissivity (ft^2/day)
Q =	pumping rate (ft^3/day)
s =	drawdown (feet)
L (u,v) =	curve function
1/u =	curve function
S =	storage coefficient, dimensionless
t =	time (days)
r =	distance from pumped well (feet)
v =	curve function
L =	leakance (^{1}/day)

Additional analyses were conducted with the method developed by Jacob (1952) using semi-logarithmic plots of drawdown vs. time which are included as Figures 3-7 and 3-8. A straight line segment is selected from each plot for this method and the change in drawdown between one log cycle is determined and substituted into equation (4) to determine transmissivity. Storage coefficient values are determined utilizing equation (5). Leakance values cannot be determined with this method.

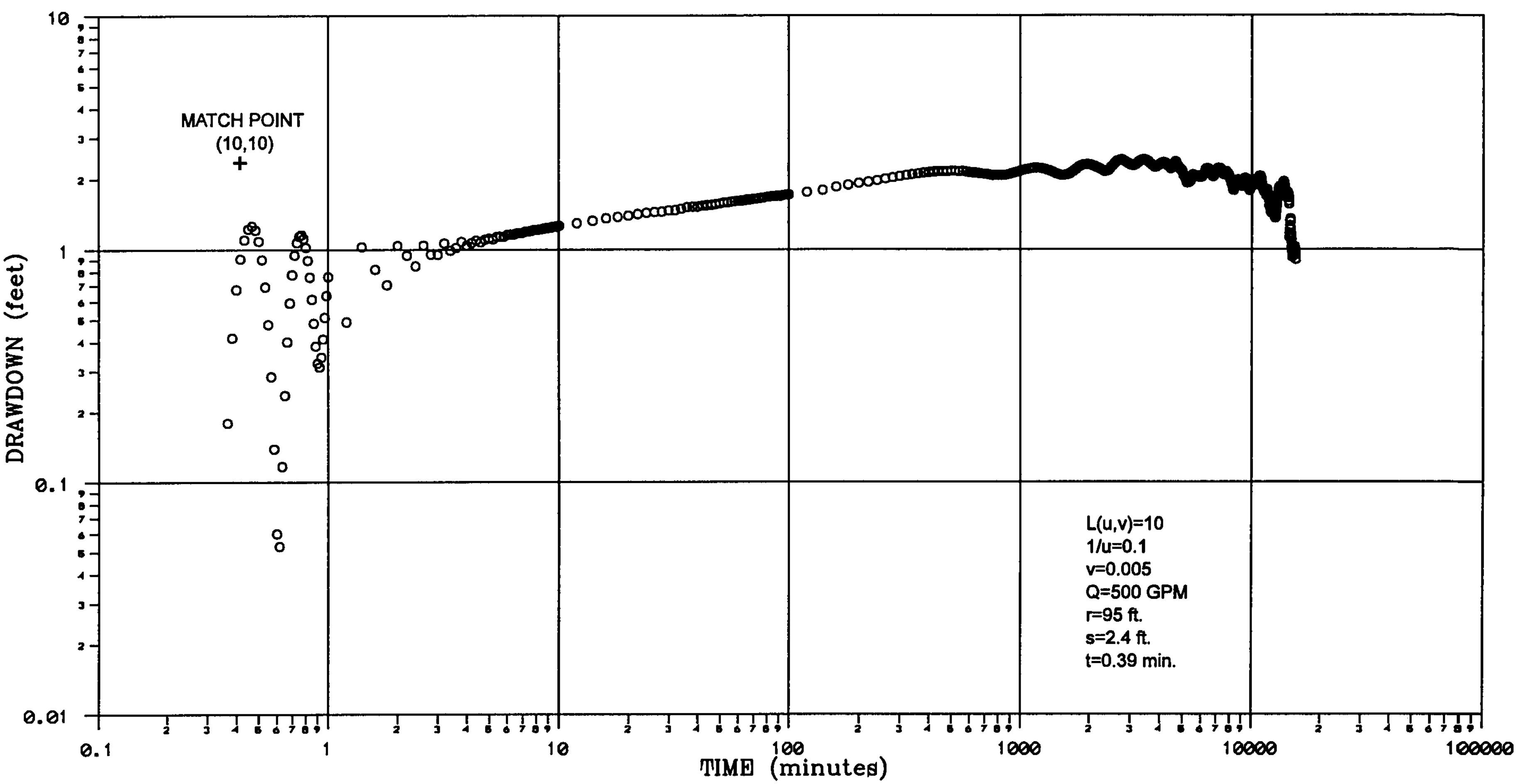

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FIGURE 3-5. Graph showing drawdown in test well R.O.TW-5 during the APT while pumping well R.O.TW-3 at 500 gpm.

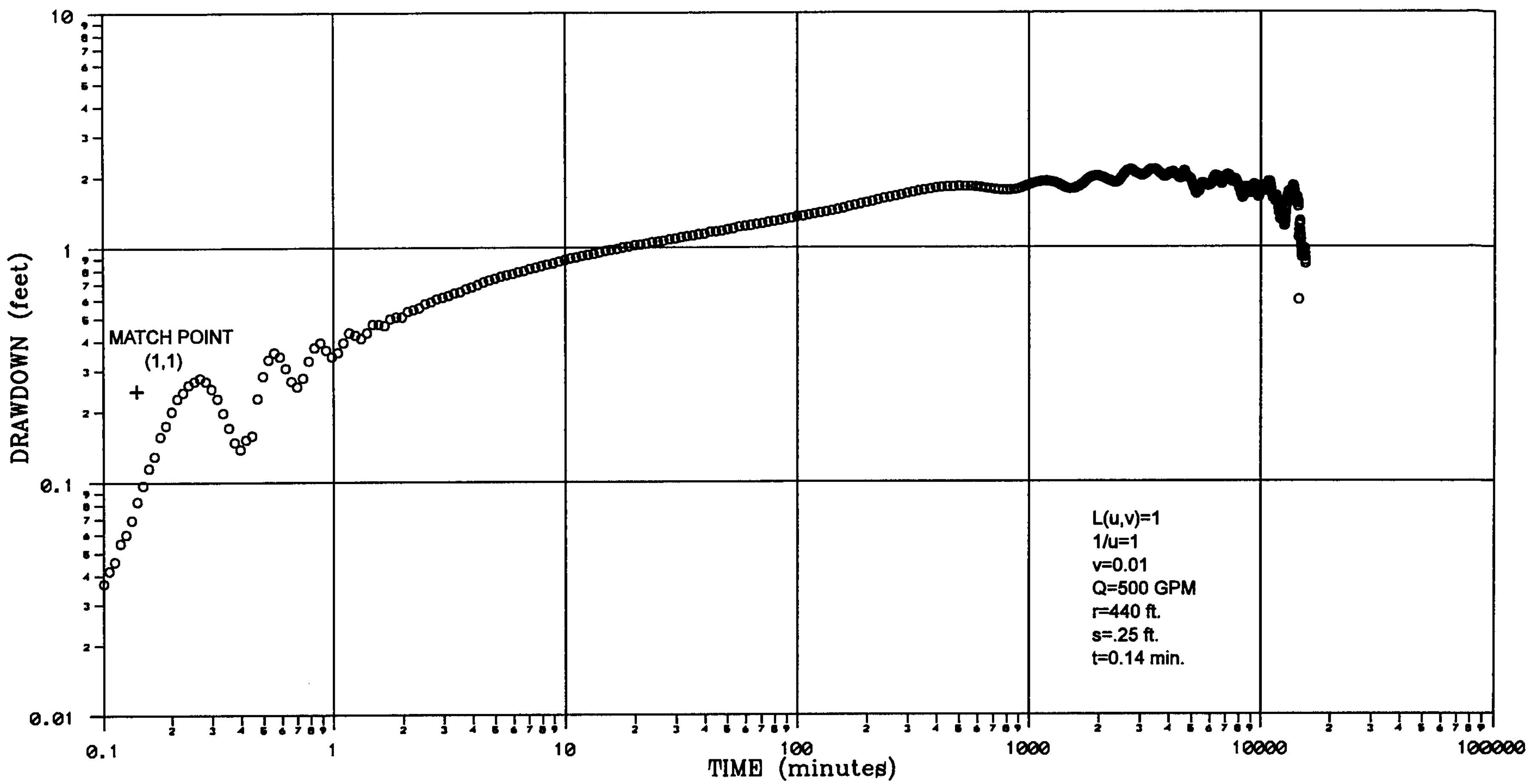

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FIGURE 3-6. Graph showing drawdown in test well R.O.TW-4 during the APT while pumping well R.O.TW-3 at 500 gpm.

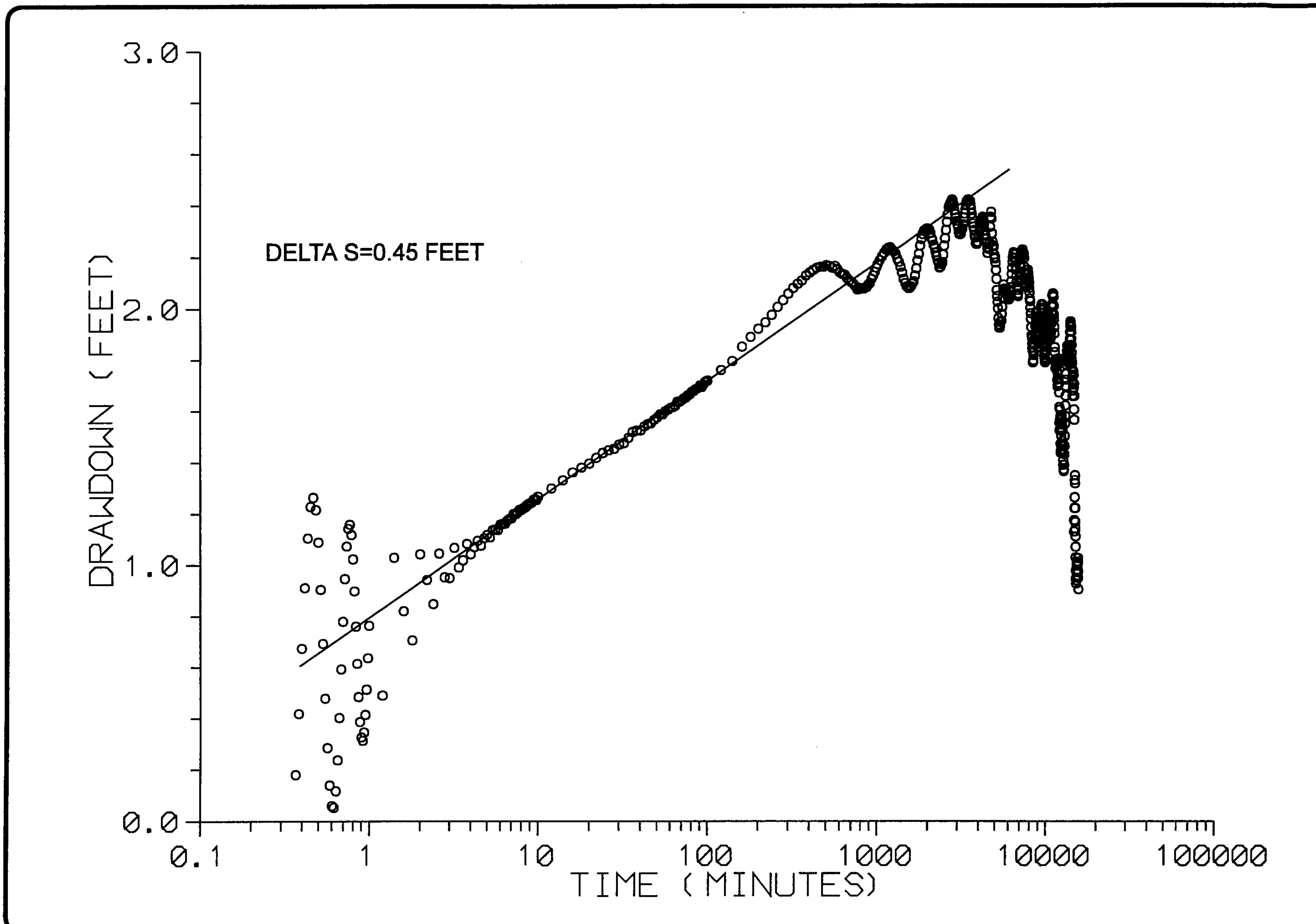

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FIGURE 3-7. Semi-Log graph showing drawdown in test well R.O.TW-5 during the APT while pumping well R.O.TW-3 at 500 gpm.

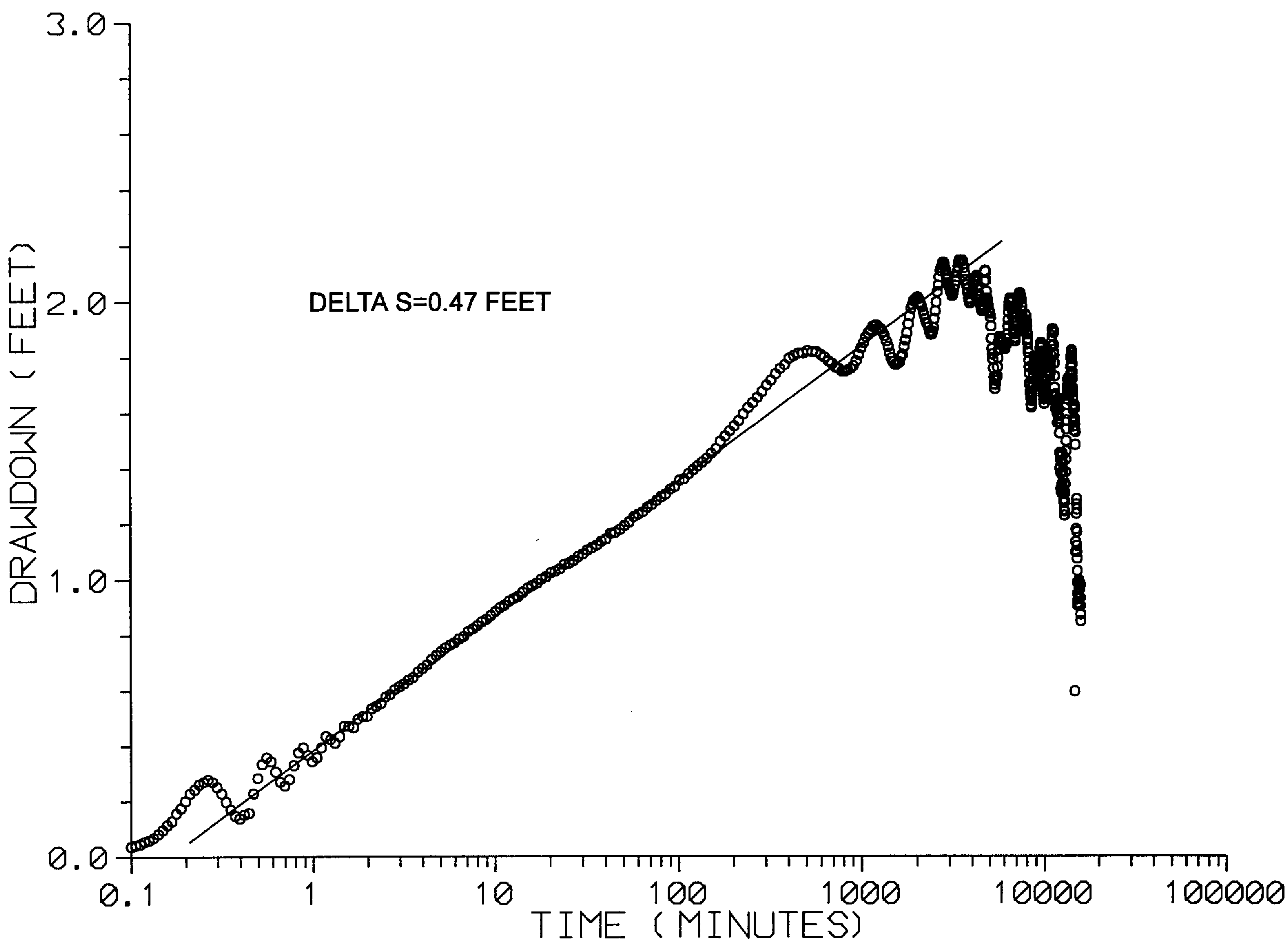

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FIGURE 3-8. Semi-Log graph showing drawdown in test well R.O.TW-4 during the APT while pumping well R.O.TW-3 at 500 gpm.

$$T = \frac{2.3\ Q}{\Delta s\ 4\pi} \qquad (4)$$

$$S = \frac{2.25\ T\ t_o}{r^2} \qquad (5)$$

where,

Δs =	head difference between log cycles (feet)
t_o =	time at zero drawdown (days)

The aquifer hydraulic coefficients calculated for the upper part of the Mid-Yorktown aquifer are summarized in Table 3-2.

3.4 Water Quality

Water samples were obtained from the test wells constructed for the investigation and subsequently analyzed for dissolved chloride concentration as a general salinity indicator. The water quality data are summarized in Table 3-3. Inspection of the table shows that the water quality is quite variable both laterally and with depth. Dissolved chloride concentrations ranged from 3700 mg/l to 10,500 mg/l in the production zone interval and up to 10,800 mg/l in underlying units. A general trend of increasing dissolved chloride concentration from west to east and with depth was noted in the samples. The increase in dissolved chloride concentration with depth is attributed to density stratification of the water within the aquifer.

3.5 Water Levels

Static water levels were measured in the reverse osmosis test wells on February 27, 1998. Measuring points were marked on top of the well casings and the elevations surveyed so the water levels could be referenced to the National Geodetic Vertical Datum of 1929. The casing top and measured water level elevations are summarized in Table 3-4. Water levels ranged from 1.10 feet NGVD in well R.O. TW-2 to 4.17 feet NGVD in well R.O. TW-8. A generally

TABLE 3-2. AQUIFER HYDRAULIC COEFFICIENTS CALCULATED FOR THE UPPER PART OF THE MID-YORKTOWN AQUIFER AT THE AQUIFER TEST SITE NEAR BUXTON, NC

CURVE MATCHING METHOD (Cooper 1963)			
Well	**Transmissivity (gpd/ft)**	**Storage Coefficient (dimensionless)**	**Leakance (gpd/ft^3)**
R.O. TW-4	230,000	6.2×10^{-5}	4.7×10^{-4}
R.O. TW-5	240,000	3.8×10^{-4}	2.6×10^{-3}
STRAIGHT-LINE METHOD (Jacob 1952)			
Well	**Transmissivity (gpd/ft)**	**Storage Coefficient (dimensionless)**	**Leakance (gpd/ft^3)**
R.O. TW-4	280,000	4.5×10^{-5}	N/A
R.O. TW-5	290,000	1.3×10^{-4}	N/A

TABLE 3-3. WATER QUALITY DATA FOR THE DARE COUNTY HATTERAS WATER SYSTEM REVERSE OSMOSIS TEST WELLS

Well	Interval Tested (feet below land surface)	Dissolved Chloride Concentration (mg/l)
R.O. TW-1*	240-275 560-588	3,800 10,000
R.O. TW-2*	246-285 625-650	8,750 10,800
R.O. TW-3	248-276	4,900
R.O. TW-4	247-278	7,460
R.O. TW-5	253-284	5,200
R.O. TW-6	282-322	6,050
R.O. TW-7	288-326	10,500
R.O. TW-8	246-329	3,700
R.O. TW-310	305-315	5,750
R.O. TW-410	400-410	6,750

* Dual zone monitor well

TABLE 3-4. WATER LEVELS IN THE DARE HATTERAS WATER SYSTEM REVERSE OSMOSIS TEST WELLS (FEBRUARY 27, 1998)

Well	Measuring Point* Elevation (NGVD)	Depth to Water (feet)	Water Level (NGVD)
R.O. TW-1	5.90	3.25	2.65
R.O. TW-2	6.88	5.78	1.10
R.O. TW-3	8.90	N/A	N/A
R.O. TW-4	6.52	4.53	1.99
R.O. TW-5	14.00	11.03	2.97
R.O. TW-6	13.42	10.76	2.66
R.O. TW-7	7.83	6.28	1.55
R.O. TW-8	7.24	3.07	4.17
R.O. TW-310	13.04	10.72	2.32
R.O. TW-410	12.92	11.31	1.61

*Measuring points are marked on the top of the well casings.

northwest to southeast groundwater flow direction with a relatively steep hydraulic gradient is indicated based on the data. Further review of the data revealed that water level elevations in wells with relatively low dissolved chloride concentrations were generally higher than those measured in the saltier wells. The water levels were converted to freshwater heads by considering density differences resulting from variations in salinity. The water levels were then compared again and a similar flow direction was indicated with a much flatter hydraulic gradient of approximately 0.5 feet per mile. The flow direction and hydraulic gradient data are as expected since the mainland recharge area is located to the northwest, the aquifer is highly transmissive, and the topography of the area is relatively flat.

4.0 HYDROGEOLOGY

4.1 Geology

The geologic descriptions provided herein are based on information obtained while drilling the reverse osmosis test wells. A stratigraphic column of the sediments encountered during the drilling of test well R.O. TW-1 is included as Figure 4-1. The descriptions and nomenclature of lithologic units given generally conform with previous work done by the U.S. Geological Survey, the North Carolina Department of Environment, Health, and Natural Resources, and various consultants including Missimer International, Inc. The focus of this investigation is on confined aquifers containing brackish water within the Yorktown Formation. Therefore, only a brief discussion of the upper stratigraphic units is presented.

The uppermost and youngest strata encountered during drilling of the test wells consist of undifferentiated marine and non-marine clastic sediments. The primary constituents include fine to coarse grained quartz sand with common shell beds and minor amounts of interbedded clay and fine grained phosphorite sand. Permeable sediments within these deposits form the water-table aquifer which is roughly 100 feet thick in the study area.

The Yorktown Formation of Pliocene age underlies the surficial sand deposits. The formation consists of beds of fine to coarse grained sand and dense clay units with sandy limestone and sandstone layers also present in some locations. Thickness of the formation can exceed 500 feet in eastern Dare County. The Yorktown Formation is described in more detail below beginning with the upper confining beds.

The upper Yorktown Formation confining beds in the study area consist of olive-gray marine clays with interbedded fine sand, shell, and phosphate material. Thickness of the confining unit ranges from approximately 115 to 150 feet in the study area. These beds have a low hydraulic conductivity and provide good confinement between the surficial sands and the underlying Mid-Yorktown Aquifer.

DARE COUNTY HATTERAS WATER SYSTEM
REVERSE OSMOSIS WELLFIELD

DEPTH IN FEET	SERIES	FORMATION	SYMBOL	LITHOLOGY	AQUIFER
	PLIO-PLEISTOCENE	UNDIFFERENTIATED		SAND, QUARTZ, FINE TO COARSE GRAINED INTERBEDDED WITH SHELL AND MINOR CLAY	WATER-TABLE AQUIFER
100	?				
200	PLIOCENE	YORKTOWN		CLAY, GRAY, PHOSPHATIC INTERBEDDED WITH SHELL LAYERS	CONFINING BEDS
300				LIMESTONE, GRAY TO YELLOWISH GRAY, SOFT TO MEDIUM HARD, HIGH PERMEABILITY IN UPPER PART OF UNIT. INTERBEDDED SANDSTONE, CLAY, AND SHELL LAYERS	MID YORKTOWN AQUIFER
400				CLAY, GRAYISH OLIVE GREEN	MID YORKTOWN AQUITARD
				SHELL, MULTICOLORED, MINOR CLAY AND SAND INTERBEDDED	
500				CLAY, GRAYISH OLIVE GREEN, SOFT, STICKY, COHESIVE, MINOR SHELL AND SAND INTERBEDDED	
600				SANDSTONE, LIGHT OLIVE GRAY, SOFT TO MEDIUM HARD, PHOSPHATIC, MINOR SHELL INTERBEDDED	LOWER YORKTOWN AQUIFER

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FIGURE 4-1. GENERALIZED STRATIGRAPHIC COLUMN OF THE SEDIMENTS UNDERLYING SOUTHERN HATTERAS ISLAND.

The Mid-Yorktown Aquifer lies beneath the upper Yorktown Formation confining beds in eastern Dare County. In most areas, the aquifer consists primarily of medium to fine grain quartz sand with occasional shell, phosphatic material, and coarse sand layers. However, a limestone facies was encountered within the aquifer in the test wells constructed during this investigation. The limestone unit is a relatively well consolidated, dark gray, biogenic, skeletal limestone with well developed secondary porosity. The upper part of the unit also contains occasional shell, sand, and phosphate as well as interbedded loosely consolidated sandstone layers. Secondary solutioning in the upper part of the aquifer has resulted in cavernous or highly permeable zones evidenced by the lost circulation problems encountered in each of the test wells during drilling. The entire thickness of the limestone unit was penetrated in test wells R.O. TW-1 and R.O. TW-2 and was found to be 167 and 166 feet, respectively.

Underlying the Mid-Yorktown Aquifer is a mixed sequence of clay, sand, and shell that forms the Mid-Yorktown Aquitard. Thickness of the unit is approximately 150 feet in the area where test drilling was conducted. Sandy clay is the predominant lithology present and thus the vertical hydraulic conductivity of the unit is low. The unit provides confinement between the Mid-Yorktown Aquifer and the Lower Yorktown Aquifer.

The final sequence encountered during drilling of the test wells was a sandstone and sand unit of the Lower Yorktown Aquifer. This unit was encountered at a depth of 557 feet in well R.O. TW-1 and at 565 feet in well R.O. TW-2. A soft to medium hard, friable sandstone is the predominant lithology. Minor amounts of shell and phosphate material are also present in the unit. The sandstone was penetrated to a depth of 650 feet in test well R.O. TW-2.

4.2 Aquifer Descriptions

The water-table aquifer is the uppermost water bearing unit on the island and by definition is unconfined or in direct contact with atmospheric pressure. Fine to coarse grained quartz sand and shell are the predominant lithologies present in the zone which attains a thickness of approximately 100 feet in the study area. This aquifer is currently the source of public supply drinking water on Hatteras Island and it is also used for domestic supply and irrigation at individual homes. Recharge to the aquifer is by direct infiltration of precipitation on the island. Discharge occurs through pumpage, evaporation, transpiration, and outflow to surface water bodies.

The Mid-Yorktown Aquifer is the proposed source of reverse osmosis feedwater on Hatteras Island and was the focus of this investigation. The aquifer occurs within a skeletal limestone facies of the Yorktown Formation. The upper part of the limestone unit is highly permeable due to secondary dissolution of the rock material. Cavernous zones were encountered during test well drilling in the upper 30 to 40 feet of the unit which caused loss of drilling fluid circulation. Aquifer tests conducted on the upper part of the limestone unit indicate that the productive capacity of the zone is very high. Transmissivity of the zone is estimated to be in the range of 230,000 to 290,000 gpd/ft based on the aquifer test results.

Recharge to the aquifer occurs on the mainland west and north of Hatteras Island, primarily from direct rainfall infiltration where the Yorktown Formation crops out at land surface or where the surface sediments are in hydraulic connection with it. In addition, some brackish water recharge occurs where the Albemarle and Pamlico Sounds intersect the recharge area of the Yorktown Aquifer. The regional hydraulic gradient within the aquifer is estimated to be approximately one foot per mile or less. Water levels measured in the reverse osmosis test wells confirm that flow direction is generally from northwest to southeast. During pumpage, additional recharge will likely be induced by vertical leakage through the overlying and underlying semi-confining units.

Water quality in the Mid-Yorktown Aquifer was evaluated based on analyses of samples obtained from the reverse osmosis test wells. Dissolved chloride concentrations varied widely from 3700 mg/l in well R.O. TW-8 to 10,500 mg/l in well R.O. TW-7. The variation in water quality within the aquifer is likely related to the relative proximities of saline surface water bodies and the distant mainland aquifer recharge areas. Density stratification of water within the aquifer is considered likely since dissolved chloride concentrations tended to increase with depth.

5.0 GROUNDWATER MODELING AND WELLFIELD DESIGN

5.1 Introduction

Groundwater modeling is a cost-effective methodology that has been widely used in practice for quantitative analysis of groundwater systems. Numerical modeling helps in understanding the hydrogeological data describing the aquifer system.

A three-dimensional numerical model for groundwater flow and solute transport has been developed to aid in the design of the Dare County Hatteras Water System brackish water wellfield. This model may be referred as the Hatteras model throughout this section of the report. The primary objective of the groundwater flow and solute transport model development is for use in evaluation of different wellfield scenarios.

The U.S. Geological Survey modular three dimensional groundwater flow simulation program, commonly known as MODFLOW (McDonald and Harbaugh, 1988) was used to develop the groundwater flow model. MODFLOW's modular structure allows great flexibility of data file structure and management. These modules allow the simulation of a variety of stresses such as pumping/injection wells, rivers and recharge. In this model, only the well package was used to simulate the flow conditions under different pumping scenarios.

In addition to the flow simulation, water quality stability is one of the major concerns that influences the design of the proposed reverse osmosis raw water supply wellfield. The computer code MT3D (Zheng, 1989) was used to simulate solute transport and hence water quality changes through time under various pumping scenarios. Similar to the structure of MODFLOW, MT3D is a three-dimensional modular computer program for solute transport simulations. The U.S. Environmental Protection Agency (EPA) initially sponsored the development of this program in 1989 and upgraded it several times since then. MT3D takes the flow file created from MODFLOW as its input. Dispersion, advection, sink/source mixing and chemical reactions are considered in MT3D.

The flow model was constructed initially from geological and aquifer hydraulic data collected in and around the Frisco/Buxton area on Hatteras Island. The model was then calibrated using data obtained from the pumping test conducted during December of 1997. The calibrated model was used to simulate the groundwater flow system and solute transport under a number of wellfield pumping scenarios. This section summarizes the construction and calibration of this model, as well as the results of four scenarios evaluated using the model.

5.2 Model Structure and Input Data

Spatial Discretization

The Hatteras model grid includes 136 rows, 96 columns and 7 layers. The spacing is irregular, with 100 feet by 100 feet grid blocks in the area of interest and up to 3000 feet by 3000 feet cells at model boundaries. This irregular spacing provides sufficient resolution at the area of interest while remaining computationally efficient. The model boundaries were set far away from the area of interest to minimize the boundary effects. The model covers an area 59,872 feet (11.34 miles) by 57,436 feet (10.87 miles). A portion of the grid used in the Hatteras model is shown in Figure 5-1.

In the vertical direction, the model is divided into seven layers, representing different hydrogeological units from land surface to a depth of about 600 feet. The definition of these layers and their general hydrogeological characteristics are shown in Table 5-1. The thicknesses of these layers, varying from 40 feet to 150 feet, were determined from borehole geological logs.

Temporal Discretization

The temporal discretization is determined from the seasonal water supply needs. According to the 1992 Water System Supply Report (Cape Hatteras Water Association, Inc, 1992), February was the minimum water use month, with an average daily water use of 0.368 MGD (million gallons per day), while August (peak tourist season) was the maximum water use month, with a daily water use of 1.087 MGD (Table 5-2). Based on the past use pattern and the projected

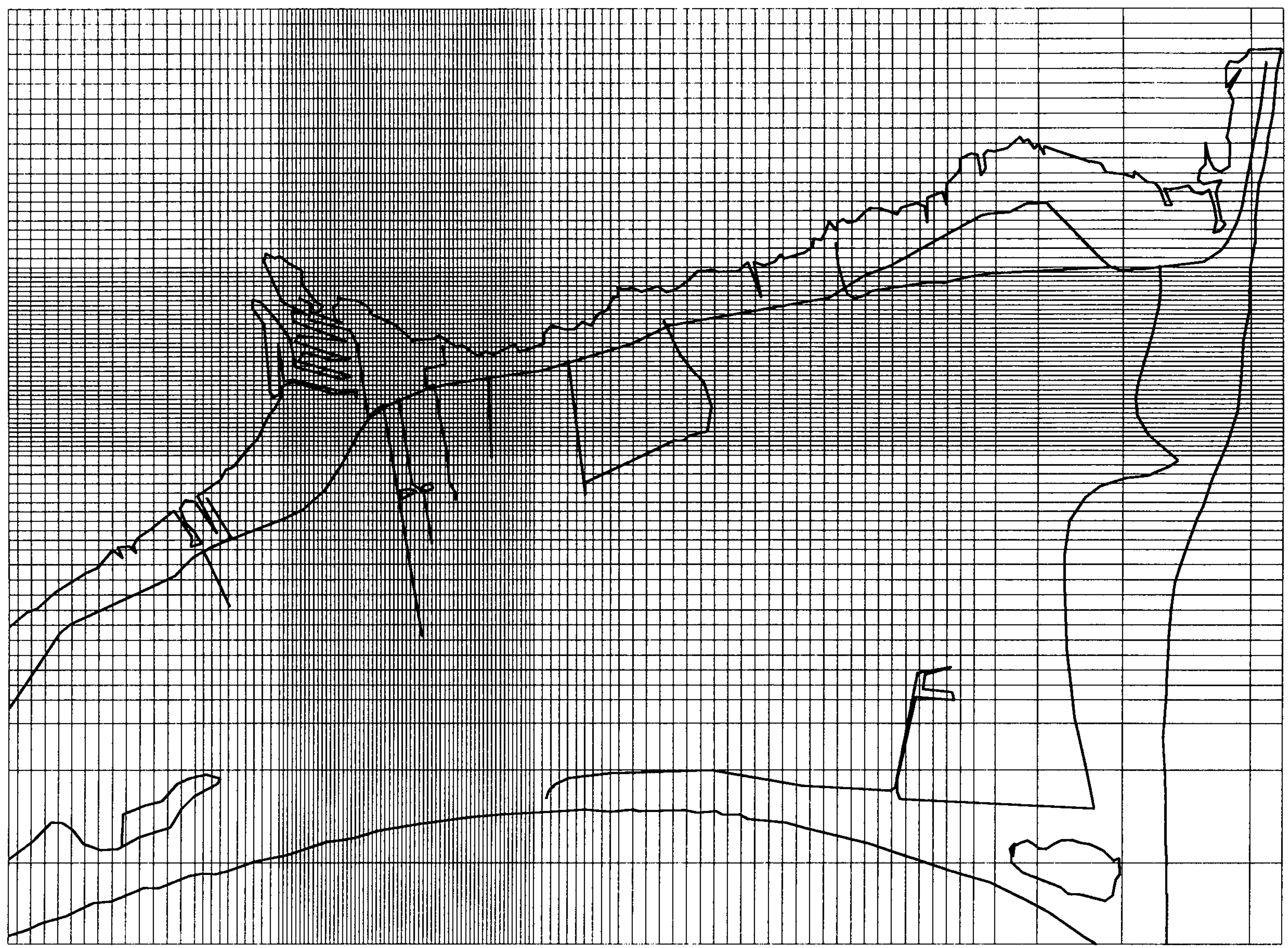

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Figure 5-1. Site map showing the grid-mesh used in the Hatteras model in the area of interest.

TABLE 5-1. Stratigraphic column of the sediments encountered during drilling of test well R.O. TW-1, and the assignment of model layers.

STRATIGRAPHIC SEQUENCE AND MODEL LAYER ASSIGNMENT

DEPTH (FEET)	*LITHOLOGY*	*AQUIFER*	*MODEL LAYER*
0	Sand, quartz, fine to coarse grained	Water-table Aquifer	1
100 200	Clay, phosphatic interbedded with shell layers	Confining Beds	2
300 400	Limestone, high permeability in the upper portion, interbedded with clay and shell layers in lower portion	Mid Yorktown Aquifer	3 4 5
500	Clay, minor sand and shell interbedded	Mid Yorktown Aquitard	6
600	Sandstone, phosphatic, shell interbedded	Lower Yorktown Aquifer	7

TABLE 5-2. 1992 WATER USE
Cape Hatteras Water Association, Inc.

Month	Withdrawal (MGD)
January	0.441
February	0.368
March	0.445
April	0.652
May	0.741
June	0.891
July	1.044
August	1.087
September	0.819
October	0.795
November	0.606
December	0.432

future use, the whole year can be divided into four stress periods (inside one stress period, the pumping rate and distribution must be the same). These stress periods are April to June, July to August, September to November, and December to March of the following year. The model simulations were run for a 30 year period, a total of 120 stress periods were considered in each scenario.

Boundary Conditions

Model boundary conditions determine the effects of the external flow system on the modeled area. Boundary conditions are expressed in mathematical equations, which represent the physical conditions to be simulated in the model. The model boundary condition specification is very important and requires an understanding of the mathematical role of boundary conditions as well as the hydrogeological relationships.

When an aquifer is surrounded by physical features such as rivers, lakes, or geological contacts of permeable or impermeable rocks, these features may be used to define the model boundaries with relative certainty. In other cases, the model size must be large enough to reduce the effect of unknown boundary conditions. A key concern is whether the stresses imposed on the system during the simulation will propagate out to the boundaries of the model system. If the hydrological stresses reach the model boundaries, it is necessary to expand the model grid and move the boundaries farther from the area of interest. The boundaries in the Hatteras model were set sufficiently distant to insure that the boundary effects on the modeling results are minimal. The model size was adjusted by trial and error at the early stage of model construction before the final model size was chosen.

The first layer (Layer 1) of the model represents the water-table aquifer system in the study area. The extent of the water-table aquifer is approximately delineated by the shorelines. The cells located on the island are assigned as active, while the cells in open water are set as constant head cells. In the bottom layer (Layer 7), representing the lower Yorktown aquifer, all cells were specified as constant head cells since the drawdown in this layer should be small and not of concern. Cells in model layers 2 through 6 were treated as active. The boundaries surrounding the model, as well as the model bottom, are treated as no-flow. Recharge and evapotranspiration are not considered in the model, because their effect is limited to the top layer of the model.

Initial Head

For a transient numerical simulation, initial head distribution of all layers needs to be specified. The initial head for all cells in the model was specified as zero. A flat water table was assumed for Layer 1, because recharge and evapotranspiration were not considered in this modeling study. Previous studies have estimated the gradient of the potentiometric surface of the Yorktown Aquifer in the Outer Banks area at approximately 0.5 to 1.0 foot decline per mile. Water levels measured in test wells tapping the production zone interval confirmed that a natural gradient of approximately 0.5 feet per mile exists in the aquifer in the study area. Regional flow in this aquifer originates in the mainland recharge areas of the aquifer and moves generally from northwest to southeast following the regional dip of the formation. A zero initial gradient was used in this model. Using a zero regional hydraulic gradient in the model gives a more conservative analysis in terms of drawdown.

Initial Concentration

The quality of water obtained from the proposed wellfield can be represented largely by the dissolved chloride concentration in the aquifer. To establish the initial distribution of dissolved chloride concentration (current situation), observed chloride concentrations from 7 wells tapping the Yorktown Aquifer were used. A statistical kriging methodology was used to establish the general trends in water quality within the aquifer system. Once the localized trends were established, a number of controlling data were added to maintain the trends in other areas where no data are available. After kriging, a value of 500 gm/l was applied to any cells whose kriged concentration was less than 500 mg/l. Figure 5-2 shows the kriged initial chloride concentration in model Layers 3 and 4. In Layer 1, the chloride concentration of all cells located under seawater was specified as 19000 mg/l while a zero concentration was given to the cells located on the island. The initial concentration of layer 2 was taken as the average of Layer 1 and Layer 3. The initial concentration of Layer 7 was a constant value of 10800 mg/l, based on water quality data obtained from test well R.O. TW-2 which taps the interval that corresponds to that

Initial Concentration of Layer 3

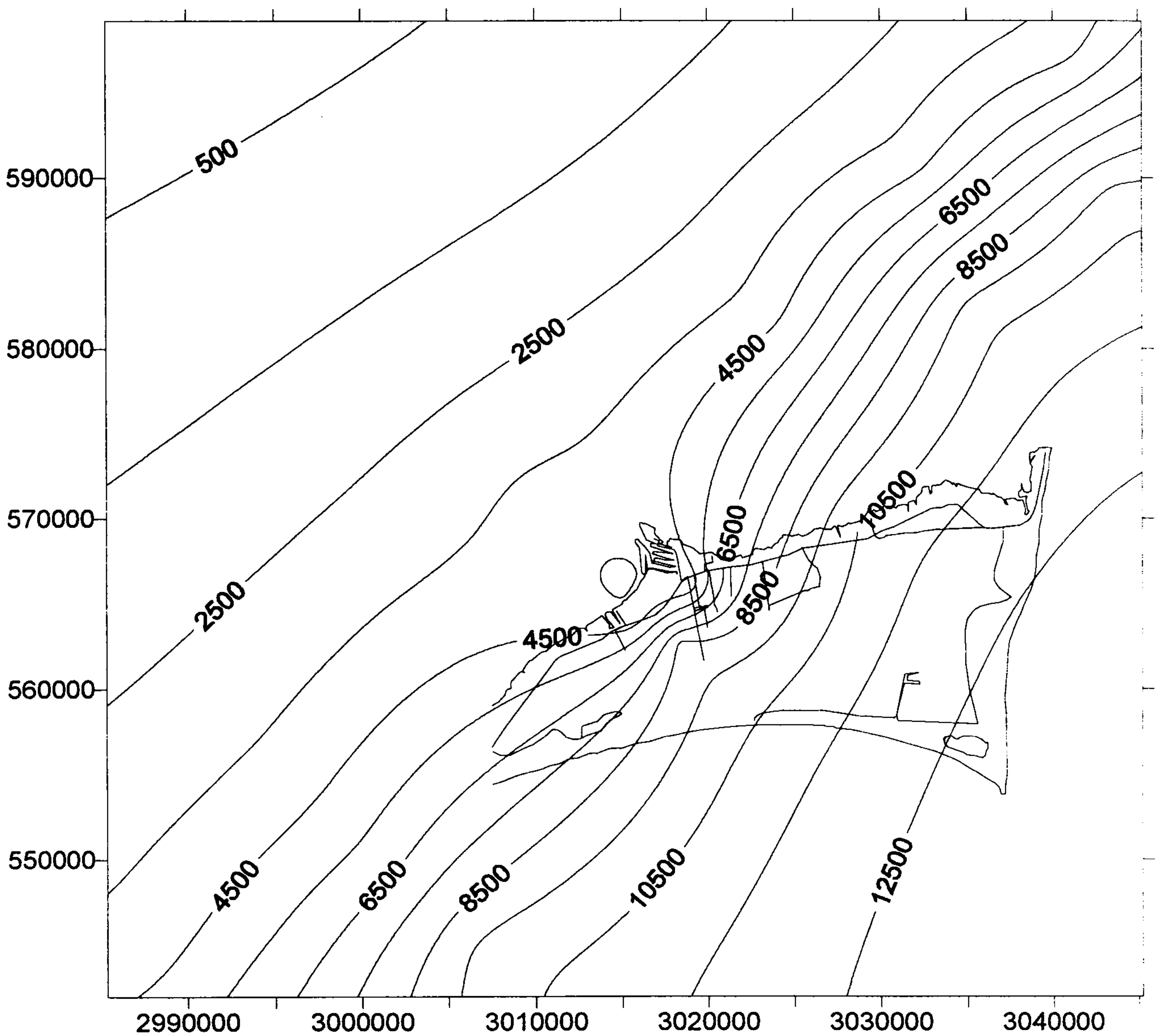

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Figure 5-2. Initial chloride concentration of model Layer 3.

layer. The initial concentration of Layer 5 was taken as the average of Layer 3 and Layer 7, and that of Layer 6 was taken as the average of Layer 5 and Layer 7.

Parameters in Solute Transport

Several parameters are required for solute transport simulations, including effective porosity and lateral and vertical dispersivity coefficients. Estimated values for these parameters were selected based on previous experience in similar hydrogeologic settings and information available in the literature.

The effective porosity can not be measured directly without core samples of the aquifer materials, but values for typical marine sediments can be used with reasonable confidence. In the Hatteras model; an effective porosity of 0.25 is used for the surficial aquifer (Layer 1), a value of 0.05 is used for the clay units (Layers 2 and 6), and an effective porosity of 0.15 is set for Layers 3 to 5 and the bottom layer.

Published data for dispersion coefficients show a very wide range of values. The value of the longitudinal dispersivity selected for Layers 1 and 7 is 10 feet, and that for Layers 3, 4, and 5 is 15 feet. A lower value, 5 feet is used for the clay-sand layer, Layers 2 and 6. Sensitivity analyses have indicated that the model result is not sensitive to the value of longitudinal dispersivity.

The values of transverse and vertical dispersivity used in the model are 0.5 and 0.1 respectively. These values are relatively high based on previous experience, and may result in an overestimate of dissolved chloride concentration in the raw water.

5.3 Model Calibration

Calibration of a flow model refers to a demonstration that the model is capable of reproducing field-measured heads and flow. Model calibration consists of adjusting model parameters within well-defined physical bounds, until the model reasonably matches field-observed data. Because no long term or regional data exist for the confined aquifer in the Hatteras area, calibration of the model was based on the constant rate aquifer performance test conducted during December, 1997. In that aquifer test, the production well (R.O. TW-3) was pumped at a constant rate of 500 gpm for approximately 11 days. Drawdowns were measured in several observation wells at different distances from the pumped well: R.O. TW-5 (95 feet from the pumping well), R.O. TW-310 (115 feet), R.O. TW-410 (115 feet) and R.O. TW-4 (440 feet).

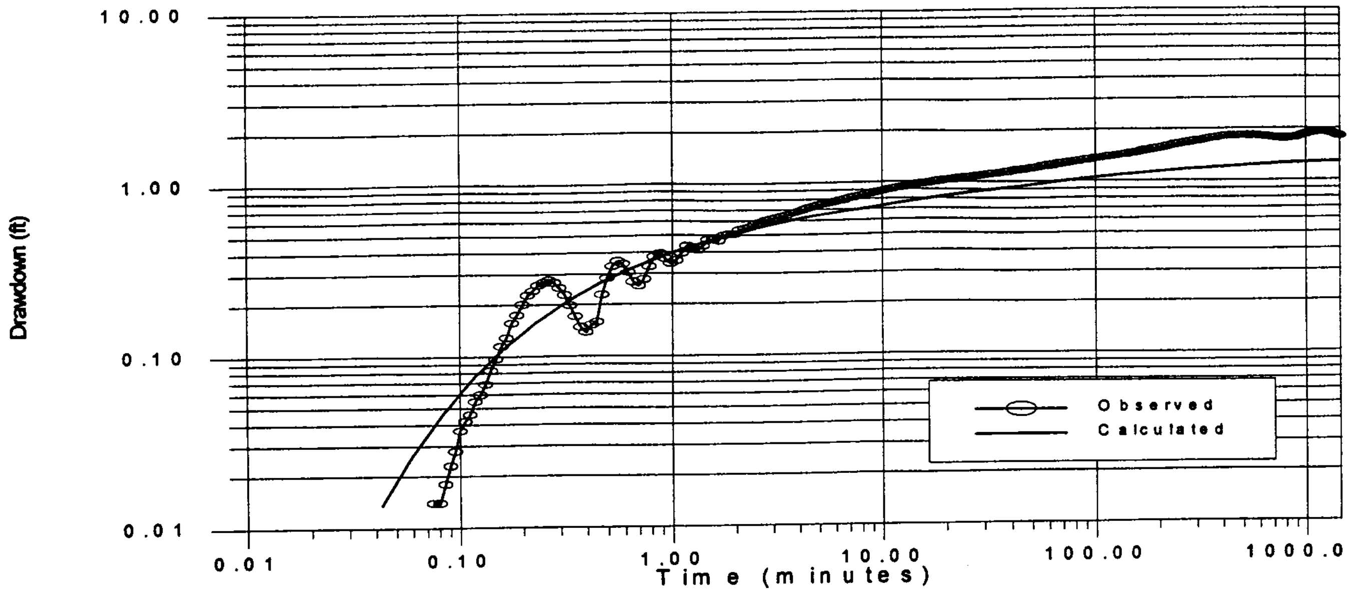
A transient flow simulation mode was constructed in which a single well was pumped at a rate of 500 gpm for a period of 24 hours. Both testing runs and field data indicate that stabilized drawdown was reached in 24 hours although the pumping test lasted for about 11 days. Calibration started with the hydraulic parameters calculated based on the field data. Adjustments were made during model calibration until the model calculated drawdown in observation wells approximately matched the observed drawdown.

The results of calibration indicate that the model is able to closely reproduce the drawdown observed during the field test. The comparison of model calculated and observed drawdown is shown in Figure 5-3. Table 5-3 lists the final calibrated model parameters, which are used in the model prediction simulations. The resultant calibrated model parameters are very similar to those calculated from the pumping test data.

5.4 Scenarios

Four scenarios were evaluated with different well locations and spacing considered in each scenario. In each case, four production wells and a 30-year simulation period were used. In these scenarios, the total pumping rate for the four wells varies seasonally, based on historic water demands. The total pumping rate also increased with time: the peak pumping rate was 2 MGD for the first ten years, 3 MGD for the second ten years and 4 MGD for the third ten years. (In Scenario 4, a pumping rate of 4.2 MGD was used in the last ten years.) Inside each stress period, the total pumping rate was equally divided among four pumping wells. The Pumping rates used in these scenarios are summarized in Table 5-4.

R.O. TW-4



R.O. TW-5

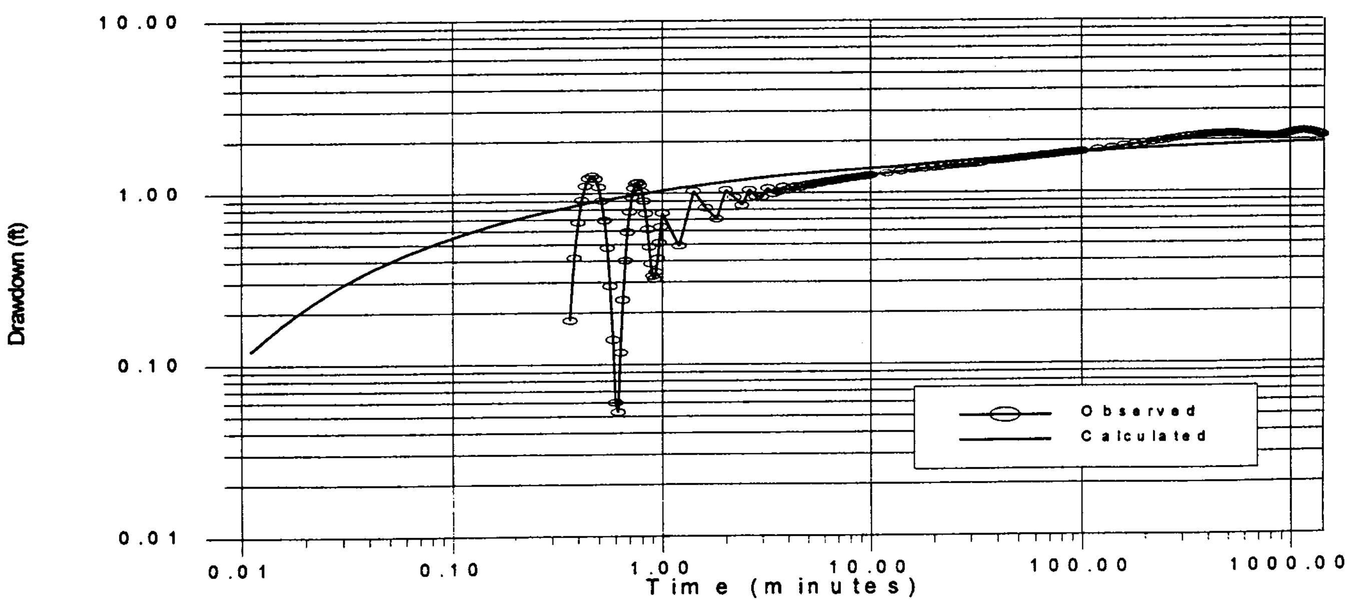


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Figure 5-3. Comparison of calculated and observed drawdown.

TABLE 5-3. MODEL PARAMETERS AFTER CALIBRATION

Layer Number	Layer Type	Layer Thickness (ft)	Transmissivity (gpd/ft)	Storage Coefficient	Underlying Vertical Leakance (1/day)
1	Unconfined	100	30.0*	0.2**	1.33e-4
2	Confined	150	1122.0	0.0001	1.33e-4
3	Confined	40	239360.0	0.00001	2.5e-2
4	Confined	40	110700.0	0.00001	1.538e-4
5	Confined	90	33660.0	0.00001	1.325e-4
6	Confined	150	11122.0	0.00001	1.332e-4
7	Confined	30	11220.0	0.000	

* Hydraulic Conductivity (ft/day)
** Specific Yield

TABLE 5-4. DARE - HATTERAS REVERSE OSMOSIS WELLFIELD MODEL SIMULATED PUMPAGE RATES

Month	Raw Water Pumpage (MGD)		
	Year 2000 - 2010	Year 2010 - 2020	Year 2020 - 2030
January	0.50	0.75	1.00
February	0.50	0.75	1.00
March	0.50	0.75	1.00
April	1.50	2.25	3.00
May	1.50	2.25	3.00
June	1.50	2.25	3.00
July	2.00	3.00	4.20
August	2.00	3.00	4.20
September	1.50	2.25	3.00
October	1.50	2.25	3.00
November	1.50	2.25	3.00
December	0.50	0.75	1.00

For treatment plant design purposes, it is necessary to provide information on the anticipated average dissolved chloride concentration of raw water from the wellfield. Average water quality from the wellfield was calculated based on the mixing of the dissolved chloride concentration of the water from each individual extraction well:

$$C_{mix} = \frac{\sum_{n=1}^{4} C_n Q_n}{\sum_{n=1}^{4} Q_n}$$

where C_{mix} is the chloride concentration after mixing. C_n is the chloride concentration from one pumping well and Q_n is the pumping rate of that well.

Scenario 1

The first scenario includes an alignment of four wells along Highway 12, extending from Water Association Road west toward Frisco. Two pumping wells are located near test wells R.O. TW-1 and R.O. TW-8, respectively. The third production well is located between these two test wells, and the forth pumping well is located approximately 2000 feet west of R.O. TW-8. The average well spacing is about 2000 feet. The locations of these four production wells are shown in Figure 5-4.

The resultant influent chloride concentration of the pumped water after 30 years is 7200 mg/l, the lowest in all the scenarios evaluated (Figure 5-5). This is primarily due to the fourth pumping well, located 2000 feet west of R.O. TW-8, which is in an area of low initial chloride concentration. This scenario would require the installation of four production wells and 6000 to 7000 linear feet of piping to transmit raw water to the proposed reverse osmosis plant.

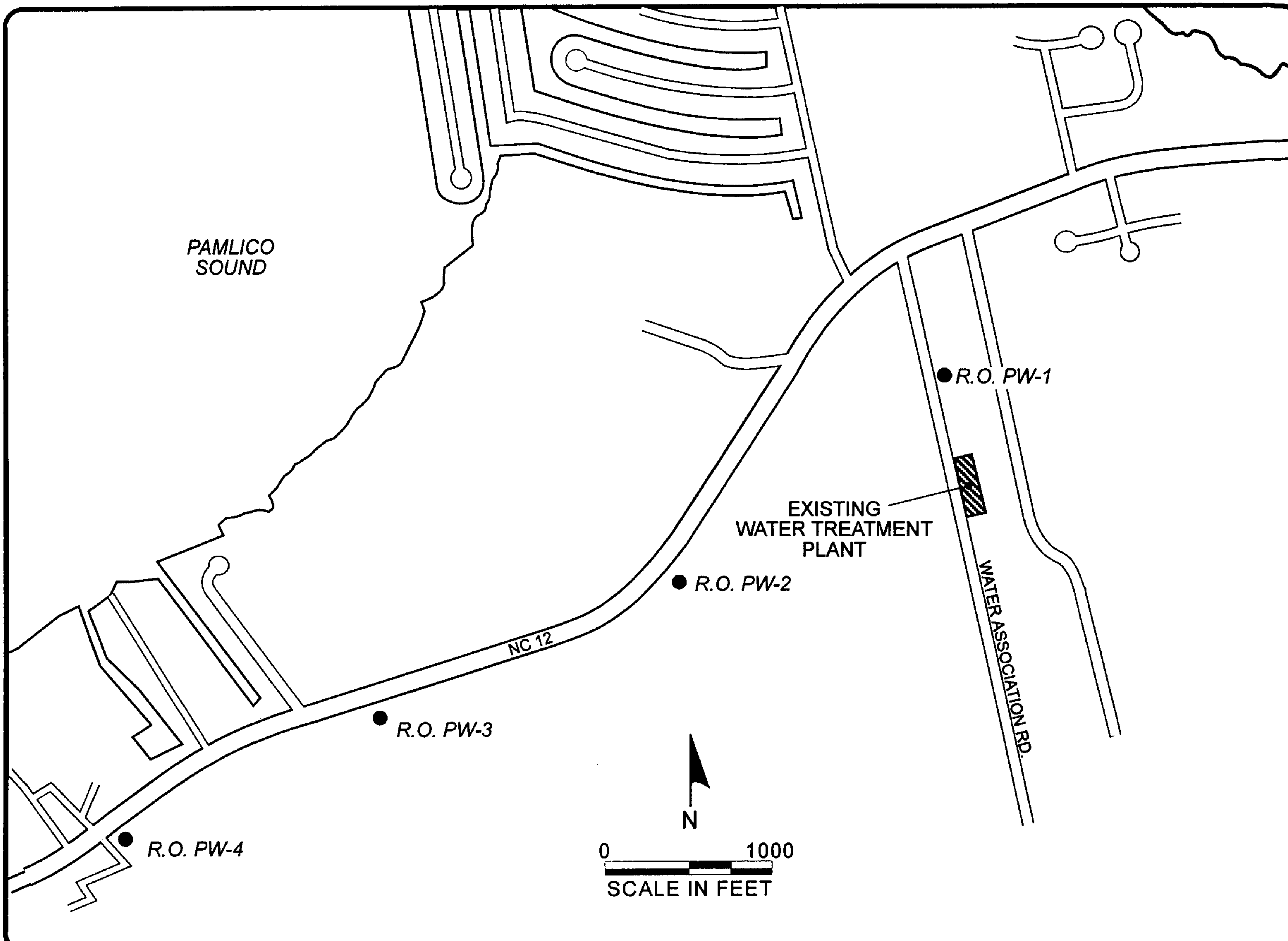

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FIGURE 5 - 4. PROPOSED R.O. PRODUCTION WELLS, SCENARIO 1

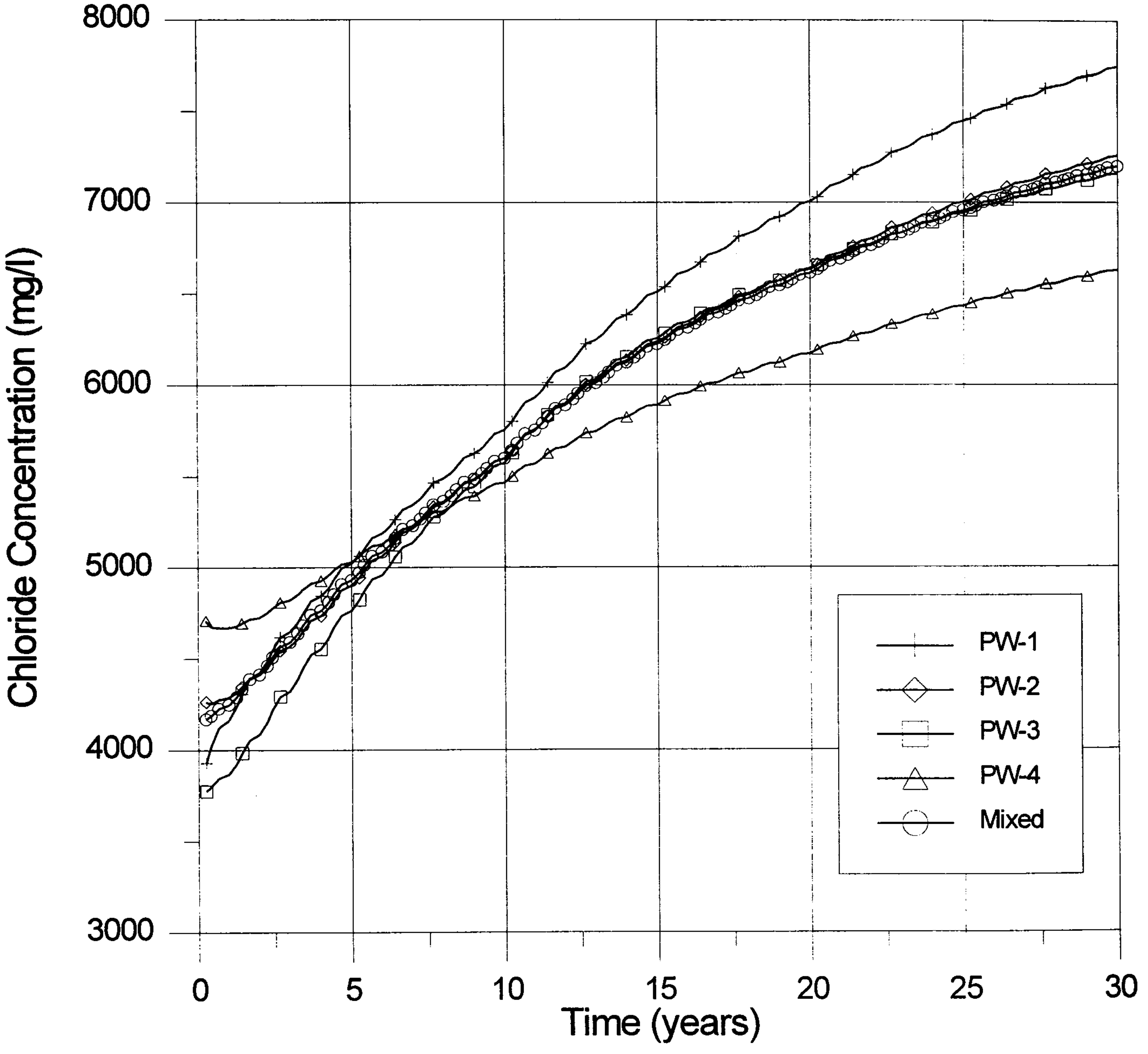

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Figure 5-5. Calculated chloride concentration of raw water from pumping wells (Scenario-1).

Scenario 2

This scenario also includes an alignment of four pumping wells with a well to well spacing of approximately 2000 feet. Two production wells are placed near test wells R.O. TW-1 and R.O. TW-8, a third production well is located adjacent to Highway 12 approximately equidistant from test wells R.O. TW-1 and R.O. TW-8, and the existing test/production well R.O. TW-3 is converted into a permanent production well. Figure 5-6 shows the locations of the proposed production wells used in this scenario.

The resultant average influent dissolved chloride concentration of the raw water after 30 years reaches 7400 mg/l (Figure 5-7). A total of three new production wells are needed. Raw water transmission piping requirements are similar to Scenario 1 but a cost savings of approximately $50,000 is realized by utilizing the existing test/production well.

Scenario 3

This scenario includes an alignment of four new production wells between the existing test wells R.O. TW-1 and R.O. TW-8 (Figure 5-8). A well to well spacing of approximately 1300 feet is used, which results in a raw water piping requirement of 5000 feet or less. The chloride concentration of the raw water after 30 years, as shown in Figure 5-9, reaches 7800 mg/l, which is the worst of the three scenarios evaluated. The primary benefit of this scenario is the reduced piping requirement.

Scenario 4

Scenario 4 is essentially the same as Scenario 2, except the maximum pumping rate for the final ten years is 4.2 MGD which is equivalent to the maximum projected demand. This scenario was selected as the most favorable by the project team based on the location of existing and proposed infrastructure, anticipated raw water quality, capital construction costs, land availability, and permitting issues. The anticipated resultant average influent dissolved chloride concentration of the raw water for 30 years is shown in Figure 5-10. The results of this scenario are similar to that of Scenario 2.

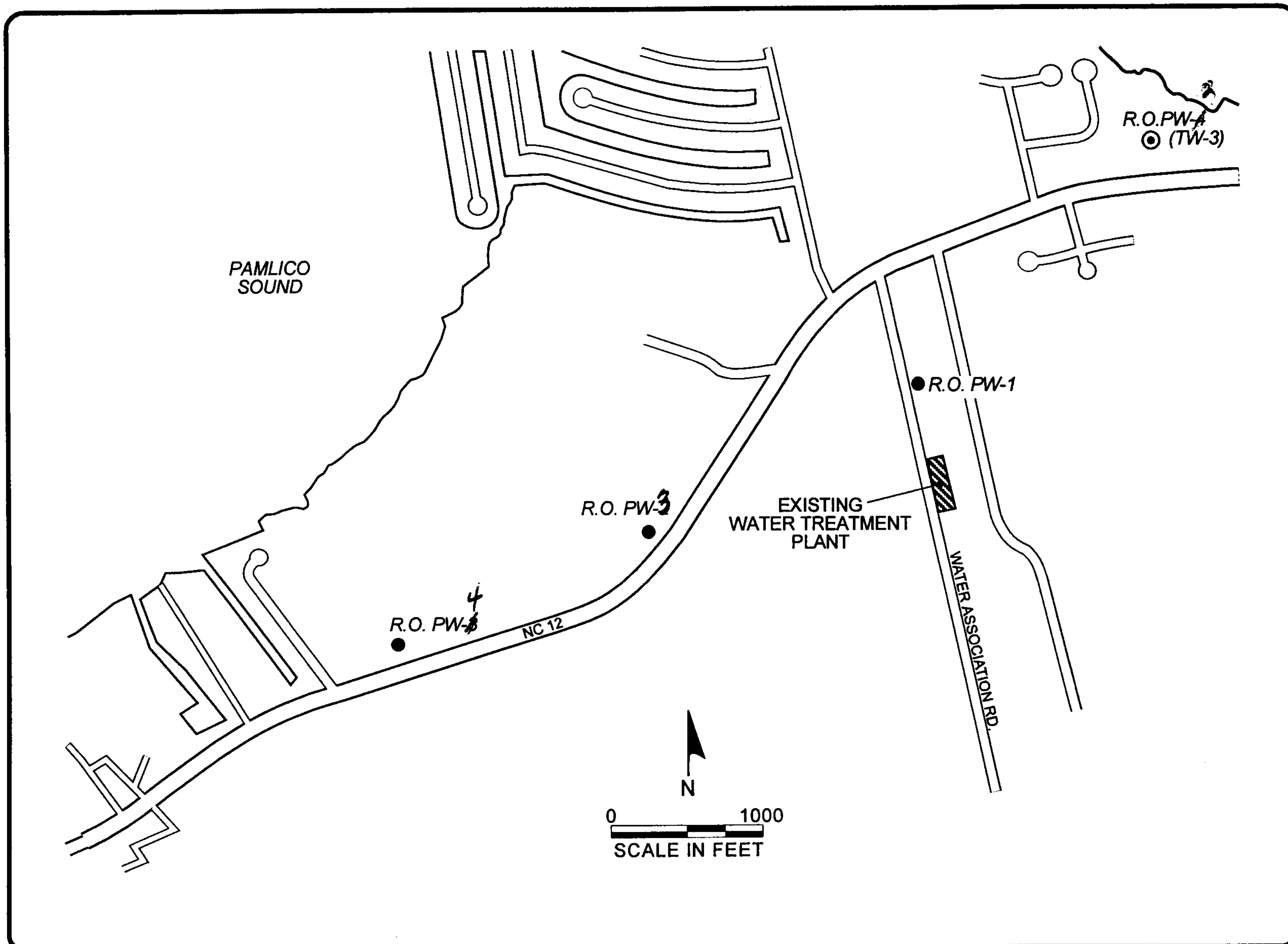

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FIGURE 5-6. PROPOSED R.O. PRODUCTION WELLS, SCENARIO 2.

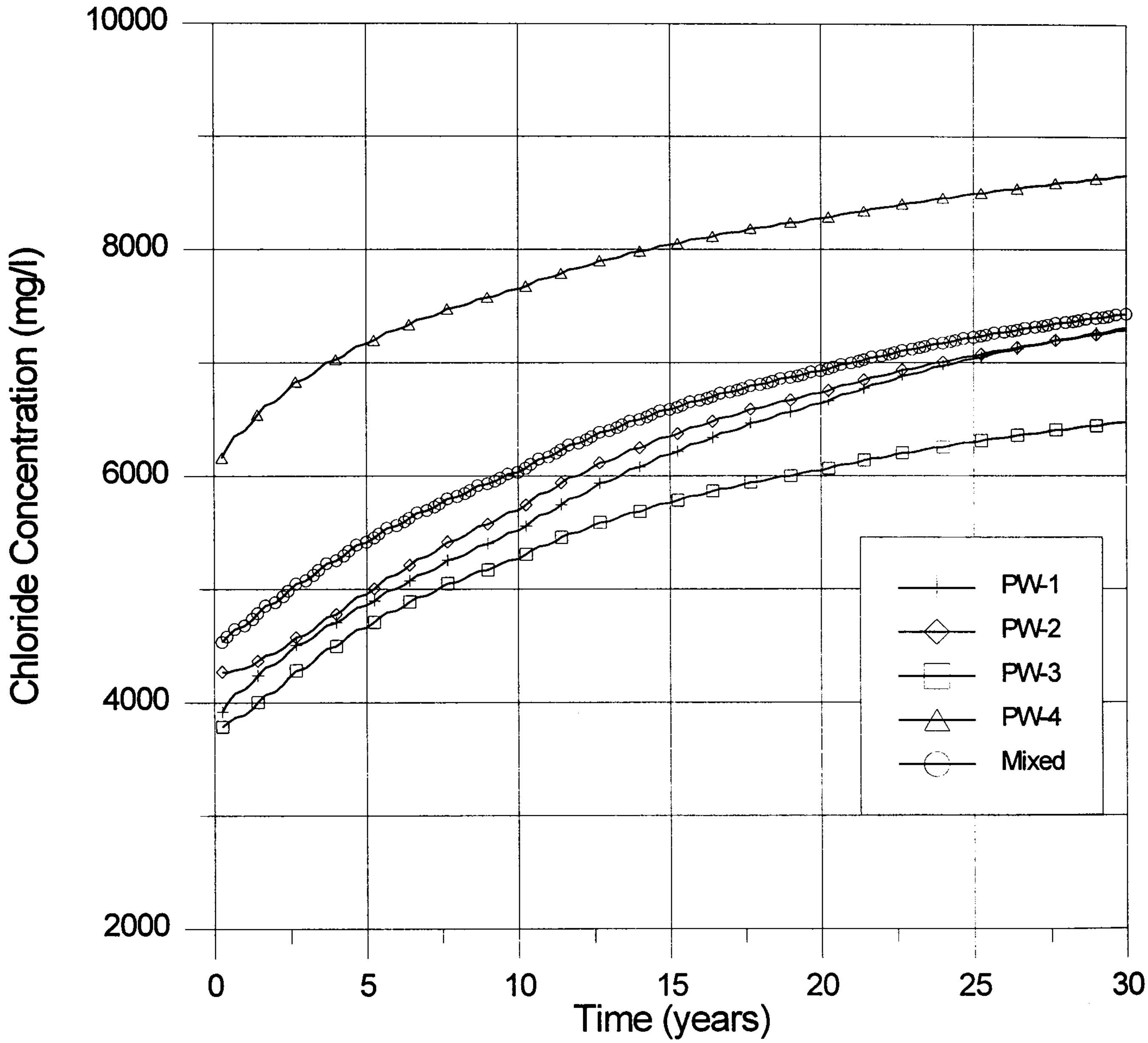

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Figure 5-7. Calculated chloride concentration of raw water from pumping wells (Scenario-2).

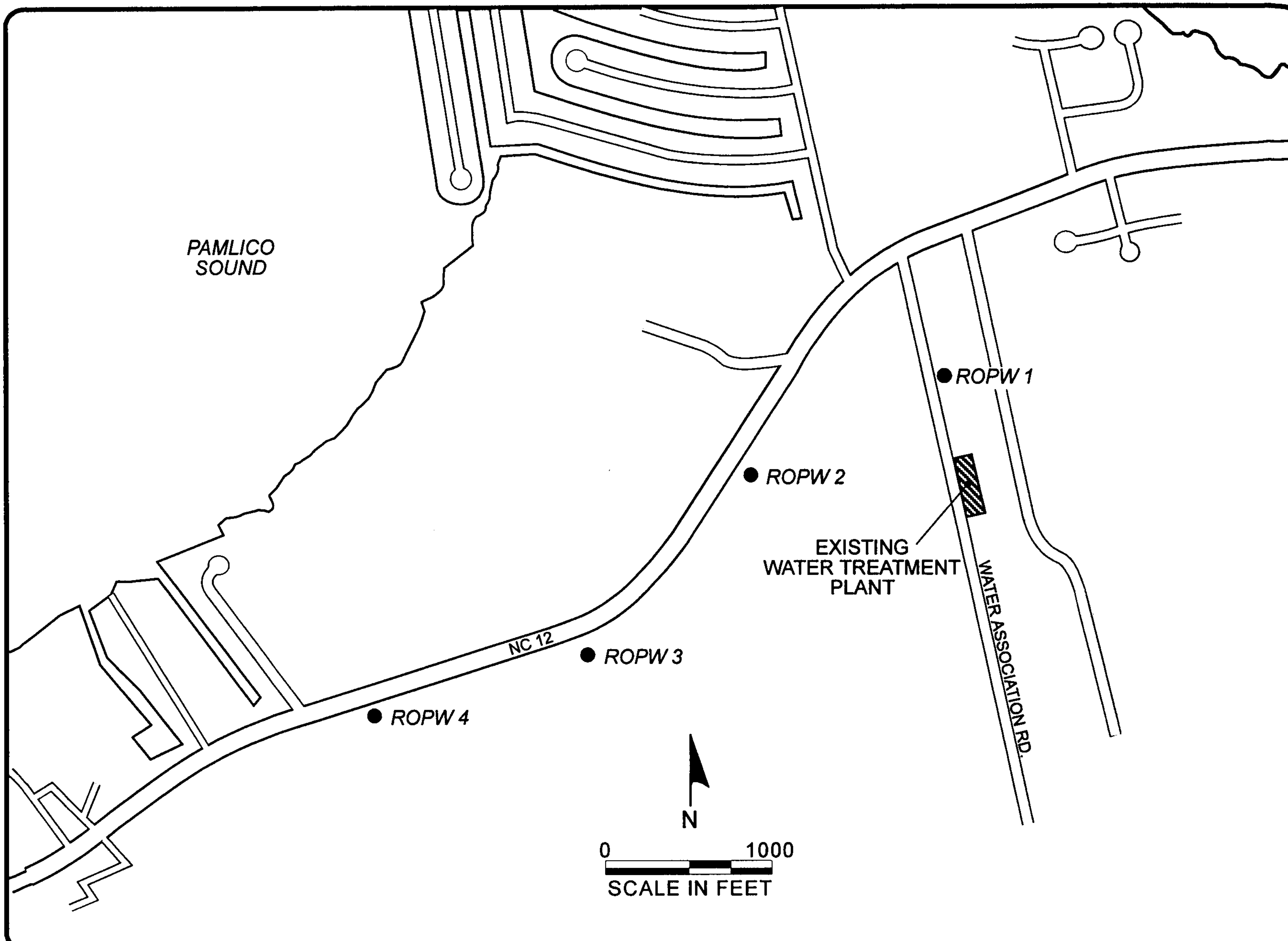

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FIGURE 5 - 8. PROPOSED R.O. WELLS, SCENARIO 3

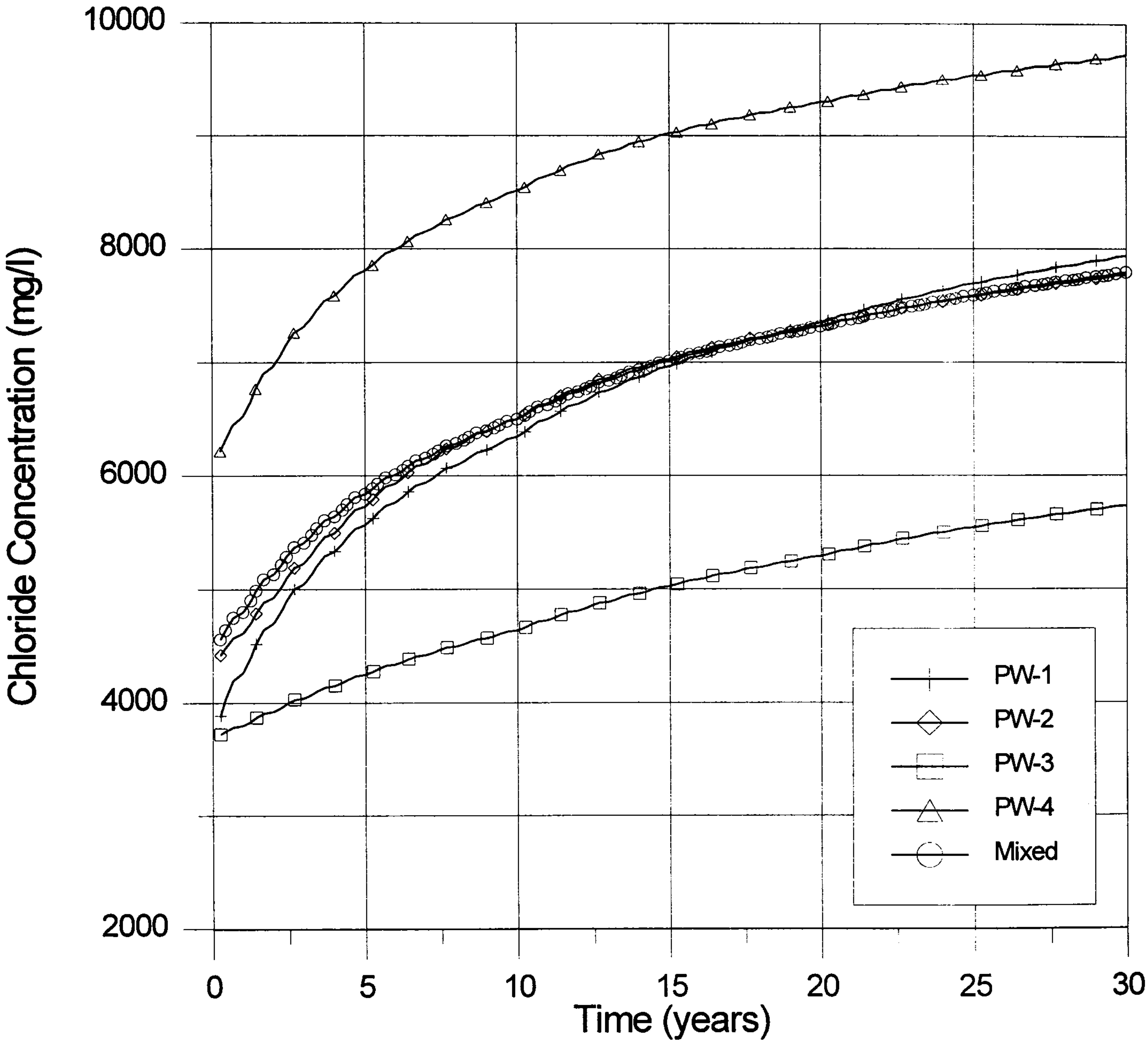

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Figure 5-9. Calculated chloride concentration of raw water from pumping wells (Scenario-3).

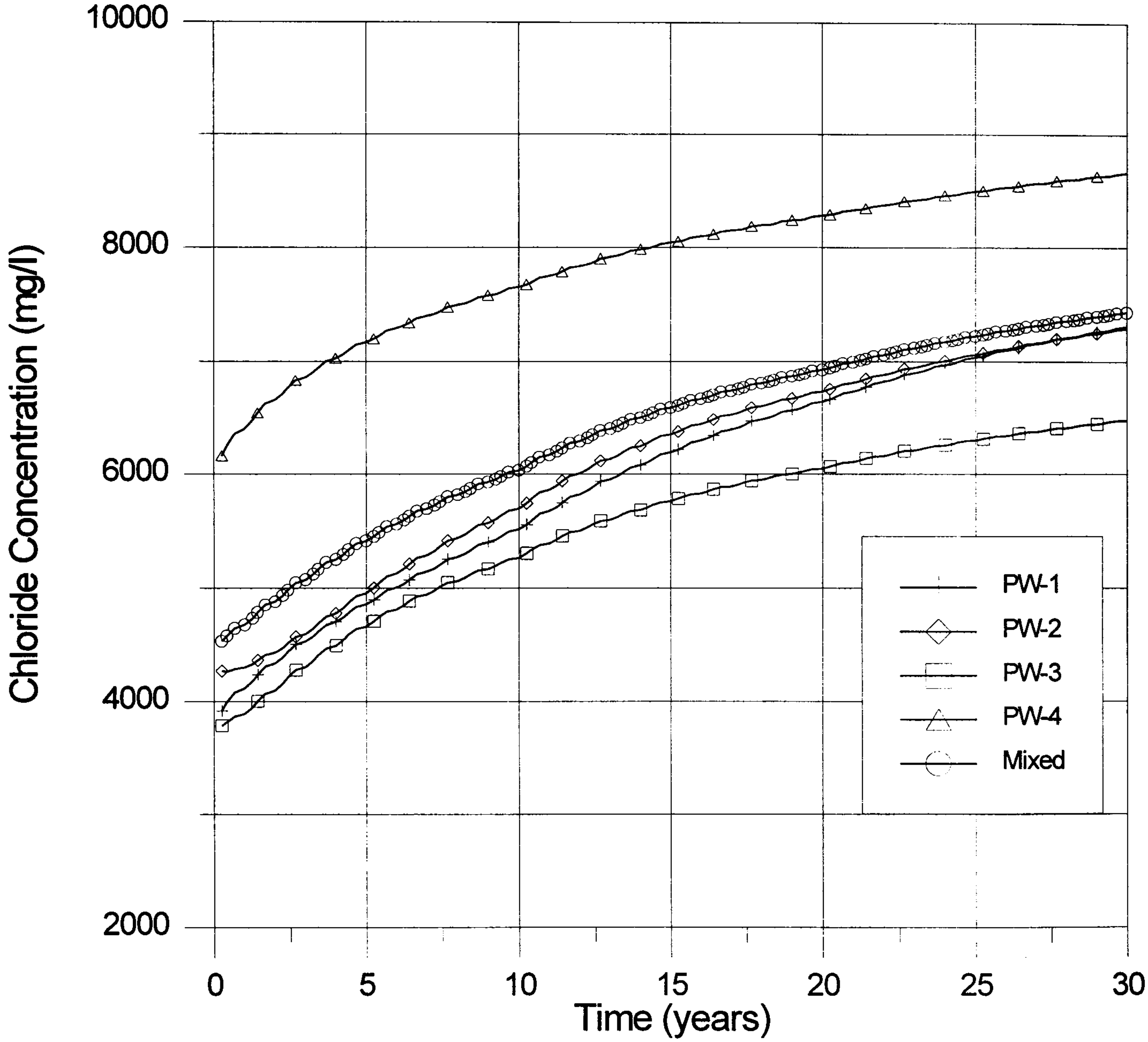

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Figure 5-10. Calculated chloride concentration of raw water from pumping wells (Scenario 4).

In all of the scenarios, the dissolved chloride concentration of the raw water increases with time. This trend indicates that groundwater with a higher dissolved chloride concentration moves towards the pumping wells from either horizontal and/or vertical directions. Flow budget analysis indicates that 52% of the pumped water is derived from lateral flow, 40% due to upward leakage from lower layers and about 8% from the top layers. The contribution from storage release is negligible because of the low storage coefficient of the aquifer and the long term simulation approaches steady state conditions. The largest contribution of water is from lateral inflow. Even with a low regional hydraulic gradient of 0.5~1.0 foot per mile, a large portion of the water will originate from the western or northwestern direction.

The drawdown due to pumping is relatively small in all of the scenarios considered. The maximum calculated drawdown of about 7 feet in the production zone interval (Layer 3), occurs in Scenario 3, because of the closer well spacing used. The maximum calculated drawdown in Layer 1 after 30 years with no recharge is about 0.5 feet. With even the lowest seasonal recharge, no discernable drawdown will occur in the surficial aquifer under the proposed production scenarios. Figure 5-11 shows model calculated drawdown in the production aquifer in the vicinity of the proposed wellfield for Scenario 4.

5.5 Sensitivity Analysis

Sensitivity analysis is an important step in model development. The purpose of a sensitivity analysis is to quantify the uncertainty in the calibrated model resulting from uncertainties in the estimates of aquifer parameters, stresses and the boundary conditions. Sensitivity analysis is typically performed by changing one parameter value at a time.

Three sensitivity analysis runs were made for the Hatteras model:

1. Sensitivity to Transmissivity of Layer 3

The model Layer 3 is the major production zone and the target aquifer for raw water supply. As shown in model calibration, the calibrated transmissivity value of this layer is very close to that

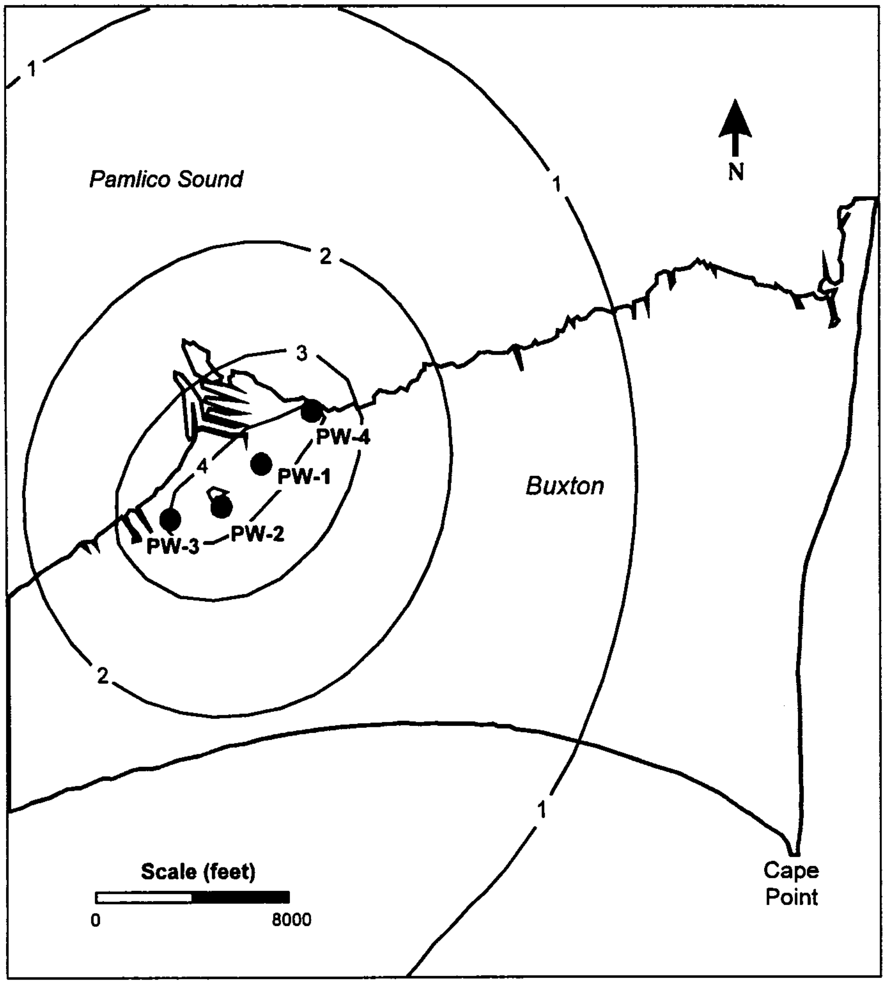

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FIGURE 5-11. PREDICTED DRAWDOWN (FEET) IN THE MID-YORKTOWN AQUIFER DUE TO FOUR WELLS PUMPING CONTINUOUSLY AT A COMBINED RATE OF 4.2 MGD obtained from the pumping test. Several runs were made to investigate the potential impact of uncertainty of transmissivity value on the prediction of raw water chloride concentration.

The results indicate that the model calculated dissolved chloride concentration of the raw water is not very sensitive to the value of transmissivity of Layer 3. Figure 5-12 shows the comparison of two runs: Scenario 4 and a similar run with the value of transmissivity of Layer 3 reduced by 50%, from 239,360 gpd/ft to 119,680 gpd/ft. The maximum drawdown in Layer 3 increased from 5 feet to 10 feet. Calculated dissolved chloride concentration of the raw water, however, is not significantly different from that determined for Scenario 4.

2. Sensitivity Analysis to Dispersivity

Dispersivity is one of the important parameters in solute transport simulations, especially when the transport process is dominated by dispersion. The value of dispersivity is difficult to measure. Dispersivities in the range 0.01 to 1.00 cm are not uncommon in laboratory experiments. However, dispersivities from two to four orders of magnitude larger are typically required for observed dispersion in field situations (Zheng and Bennett, 1995). Studies have shown that dispersivities are scale-dependent, due to the heterogeneity of porous media (Dominico and Schwartz, 1990).

In the model runs, dispersivities ranging from 5 feet to 15 feet were used. In the sensitivity analysis run, the dispersivity value for each layer was increased by a factor of 10. Results of the sensitivity analysis show that the dissolved chloride concentration of the raw water after 30 years reaches 7800 mg/l, which is only about 5% higher than that in Scenario 4 (Figure 5-13). This indicates that the predicted dissolved chloride concentration is not very sensitive to the dispersivity values within the range tested. It may also imply that the transport process is controlled by advection.

3. Sensitivity Analysis to Initial Chloride Concentration

The third sensitivity analysis was to evaluate the water quality changes over the 30 year period if the initial chloride concentration is 1.5 times greater in deep layers (Layers 4, 5, 6, and 7).

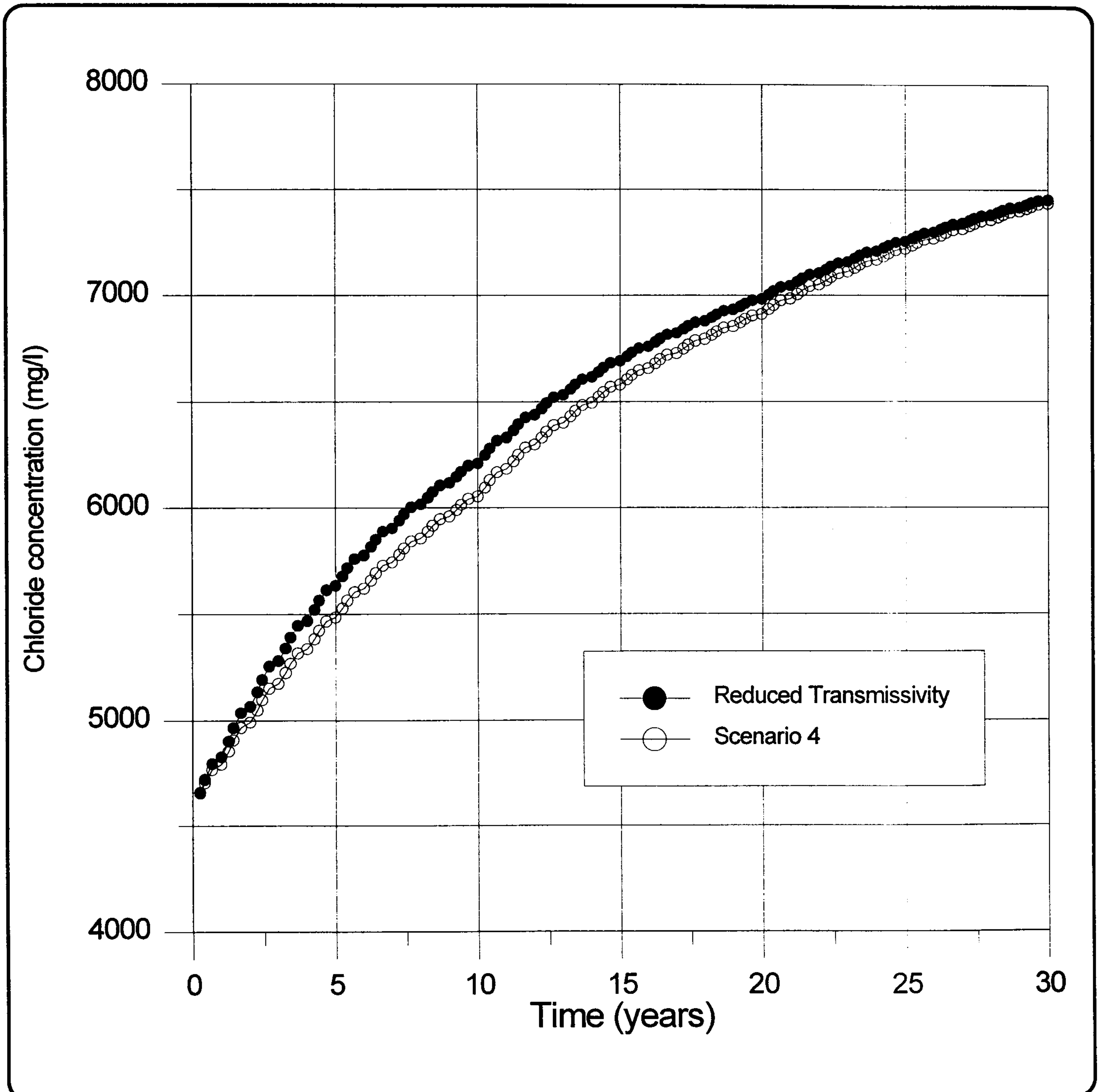

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Figure 5-12. Sensitivity analysis for transmissivity of Layer 3. A reduction of 50% from the Calibrated model.

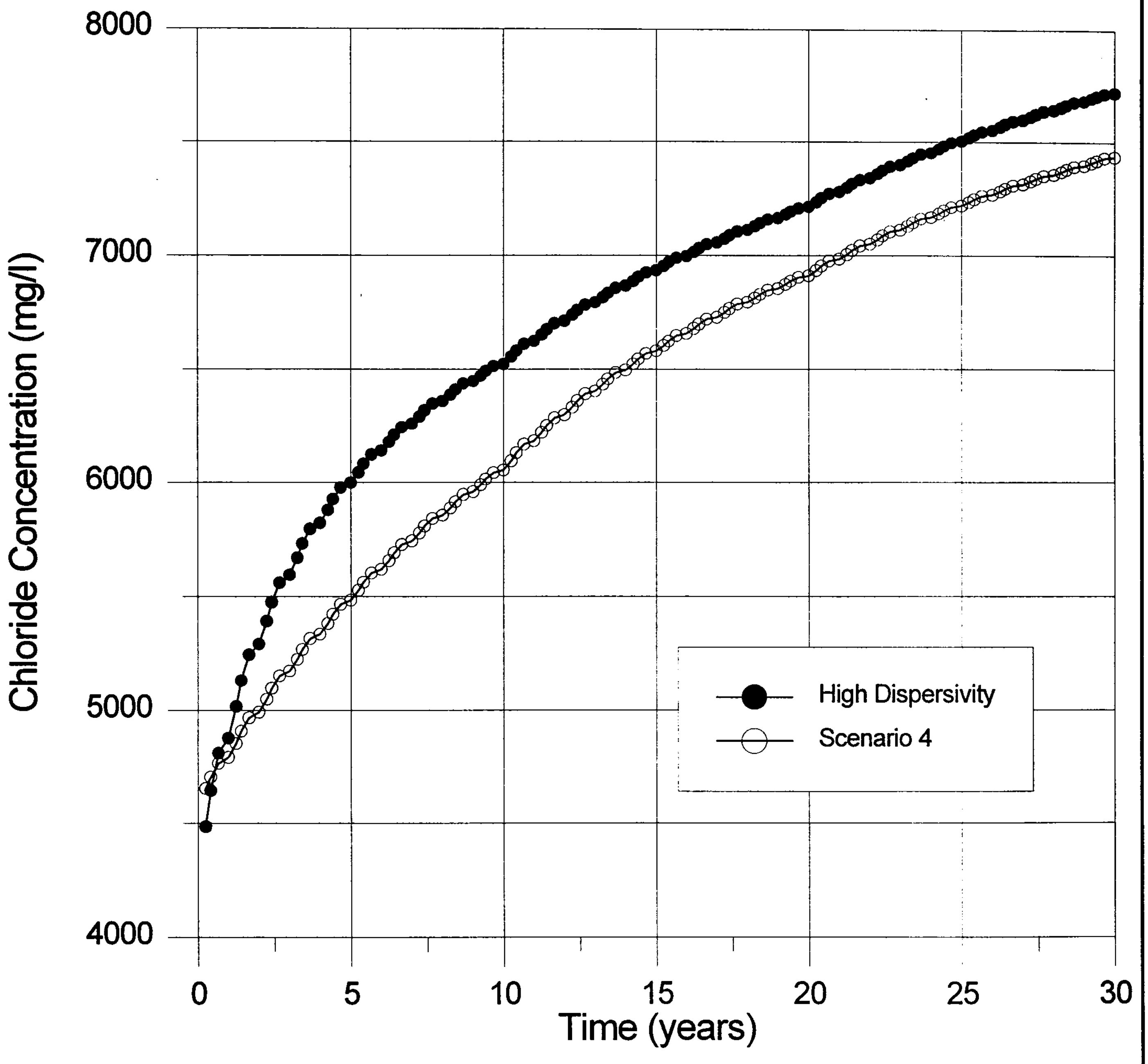

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Figure 5-13. Sensitivity analysis of dispersivity. A ten-fold increase of the values used in the calibrated model.

Since the model result is a numerical solution of partial differential equations with specified boundary and initial conditions, changes of the initial chloride concentration near the proposed wellfield should significantly affect the model results.

Very little data exist for dissolved chloride concentration in deep layers. Although the chloride concentration distribution near the wellfield was estimated based on several samples collected in the production aquifer, there was only one sample from the Layer 7 interval. The initial chloride concentrations of Layers 4, 5 and 6 were determined based on monitor well data and range between the chloride concentrations of Layer 3 and Layer 7. Flow budget analysis indicated that 42% of the pumped water originates from these deep layers. Therefore, the uncertainty in initial concentration estimates should be considered.

In this sensitivity analysis, the initial chloride concentrations of Layers 4 through 7 were increased by a factor of 1.5, and the wellfield configuration and pumping schedule were the same as Scenario 4. Figure 5-14 shows the calculated chloride concentration of raw water over a 30 year period. As a comparison, the result of Scenario 4 is also shown in this figure. The mixed concentration is elevated to 9600 mg/l at the end of simulation. This is a 29% increase in chloride concentration of the raw water, resulting from an initial concentration in deep layers increased by 50%.

5.6 Discussion of Model Results

The results of the computer modeling show that deterioration of water quality in the Mid-Yorktown aquifer will occur with time due to pumpage, when water with a higher dissolved chloride concentration moves into the pumping wells. The change of water quality will be a gradual process. Within the 30 year simulation period, the dissolved chloride concentration of raw water should remain below 8000 mg/l based on the proposed wellfield design and pumpage rates. Sensitivity analyses indicate that the modeling results are not very sensitive to the transmissivity of the production aquifer or to dispersivity. However, the model results are sensitive to underlying and laterally variant water quality for which little data exist.

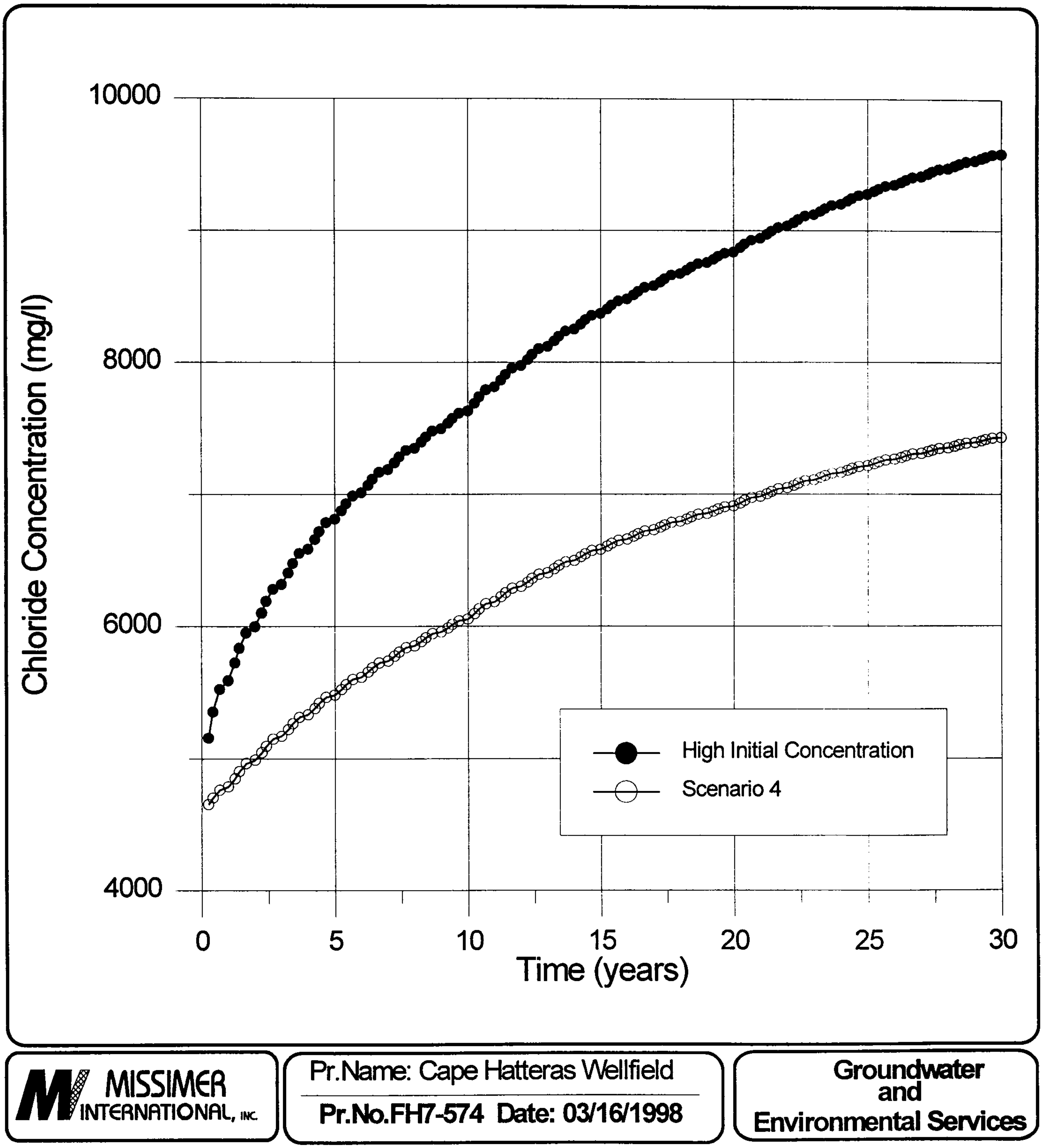

Figure 5-14. Sensitivity analysis to higher initial choride concentration deep layers (Layers 4 - 7). Initial chloride concentration was increased 1.5 times from Scenario 4.

The locations of the proposed R.O. supply wells were selected primarily based on water quality conditions in the production zone interval, economics and location of existing infrastructure. Within the test program, test well R.O. TW-8 had the best water quality. The construction of an additional test well to the west of R.O. TW-8 would confirm if the trend of decreasing dissolved chloride concentration to the west continues.

Drawdown in the production aquifer, induced by the proposed pumpage, is low. The drawdown in the surficial aquifer, induced by the proposed pumpage, is negligible and indiscernible in the field. In actuality, water levels in the surficial aquifer will likely increase after the reverse osmosis plant becomes operational due to the reduction in pumpage from the shallow aquifer.

5.7 Wellfield Configuration

A wellfield capable of producing 4.2 MGD of raw water is required to supply the proposed reverse osmosis plant. The plant will be capable of producing 2.1 MGD of product water at a recovery efficiency of 50%. Four wells each pumping at approximately 700 gpm are required to produce the desired withdrawal amount. The scenario selected for construction of the wellfield includes an alignment of wells along Highway 12 near Water Association Road with a spacing of approximately 2000 feet between wells. Production wells should be placed near test wells R.O. TW-1 and R.O. TW-8 with an additional production well placed midway in between these two test wells. Test/production well R.O. TW-3 should be converted to permanent production well status. Further wellfield expansion is recommended if raw water pumpage rates in excess of 4.2 MGD are desired.

5.8 Production Well Design

Design recommendations for the proposed production wells are based on desired pumping rates, state well construction requirements, general guidelines for reverse osmosis supply wells, and site specific information obtained during test well construction.

The production wells should be constructed with 12-inch diameter SDR 17 PVC casings extending to a depth of approximately 250 feet below land surface. If necessary based on site conditions, an 18-inch diameter surface casing should be installed to a depth of at least 40 feet below land surface to prevent caving in the upper part of the hole during drilling. Total depths of the wells should be 300 feet below land surface or less. A hydrogeologist should supervise the construction activities and recommend specific cased and total depths for each well based on lithologic analysis of formation samples obtained during drilling. The open hole sections of the wells should be drilled utilizing the reverse air technique. No drilling fluid, other than clear water, should be used in the production zone. A schematic diagram showing the proposed construction details for the wells is provided as Figure 5-15. The new production wells and existing test/production well R.O. TW-3 should be thoroughly developed with compressed air to remove drill cuttings and sediment from the open boreholes.

Step-drawdown pump tests should be conducted on the new production wells after they are completed to assess individual well yields. The wells should be disinfected following development and pump testing. Submersible pumps powered by variable frequency drive motors should be installed in the wells with the intakes set at 30 to 40 feet below land surface. Pumping water levels are not anticipated to exceed 20 feet below land surface. Setting the pumps slightly deeper than required will allow for potential well yield deterioration with time that may occur due to the deposition of calcium carbonate on the borehole walls. Recommended withdrawal rates for the production wells range from 350 to 750 gpm depending upon seasonal demand.

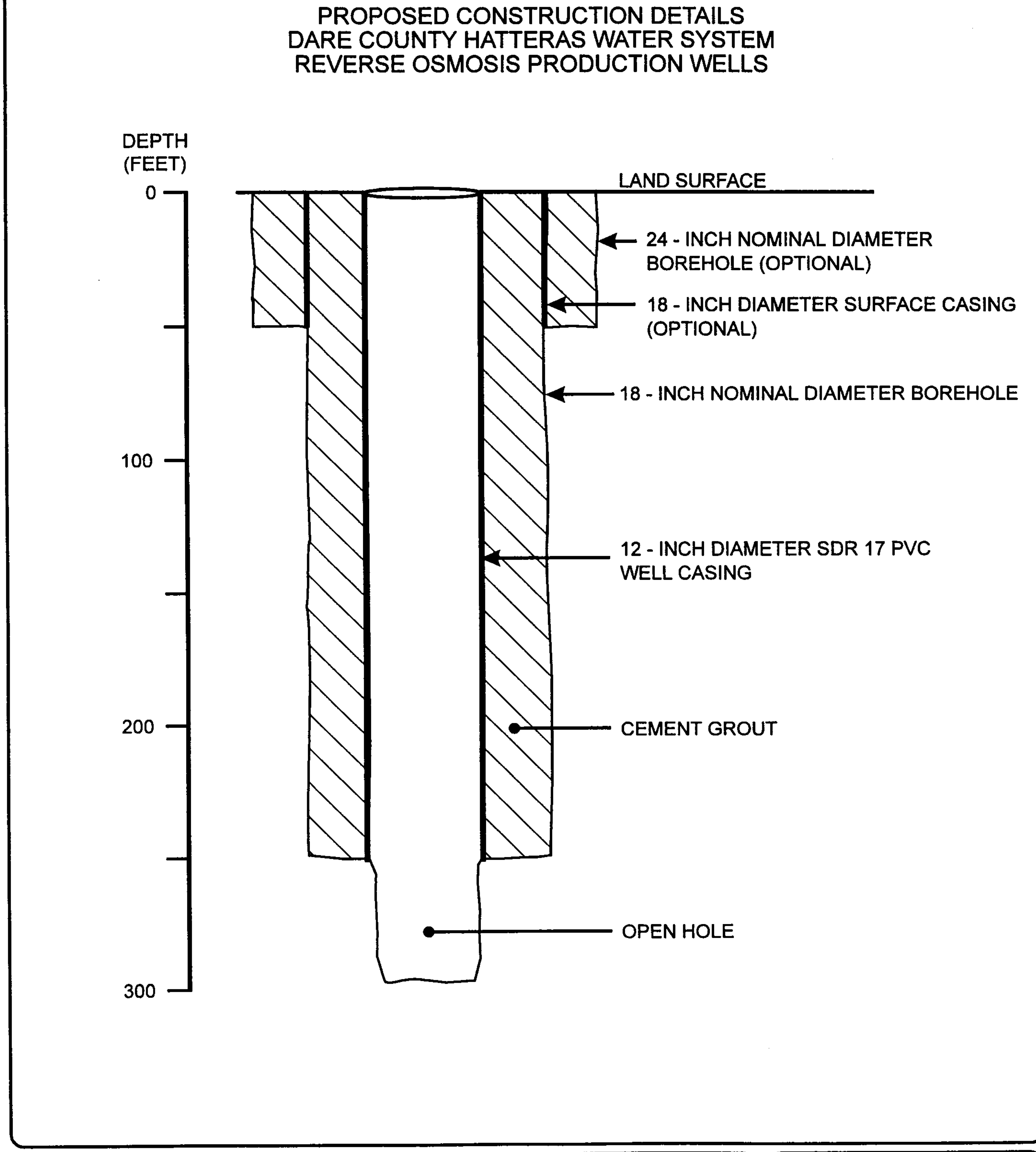

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FIGURE 5-15. SCHEMATIC DIAGRAM SHOWING GENERAL CONSTRUCTION DETAILS FOR PROPOSED REVERSE OSMOSIS PRODUCTION WELLS. CASED AND TOTAL DEPTHS OF THE WELLS MAY VARY.

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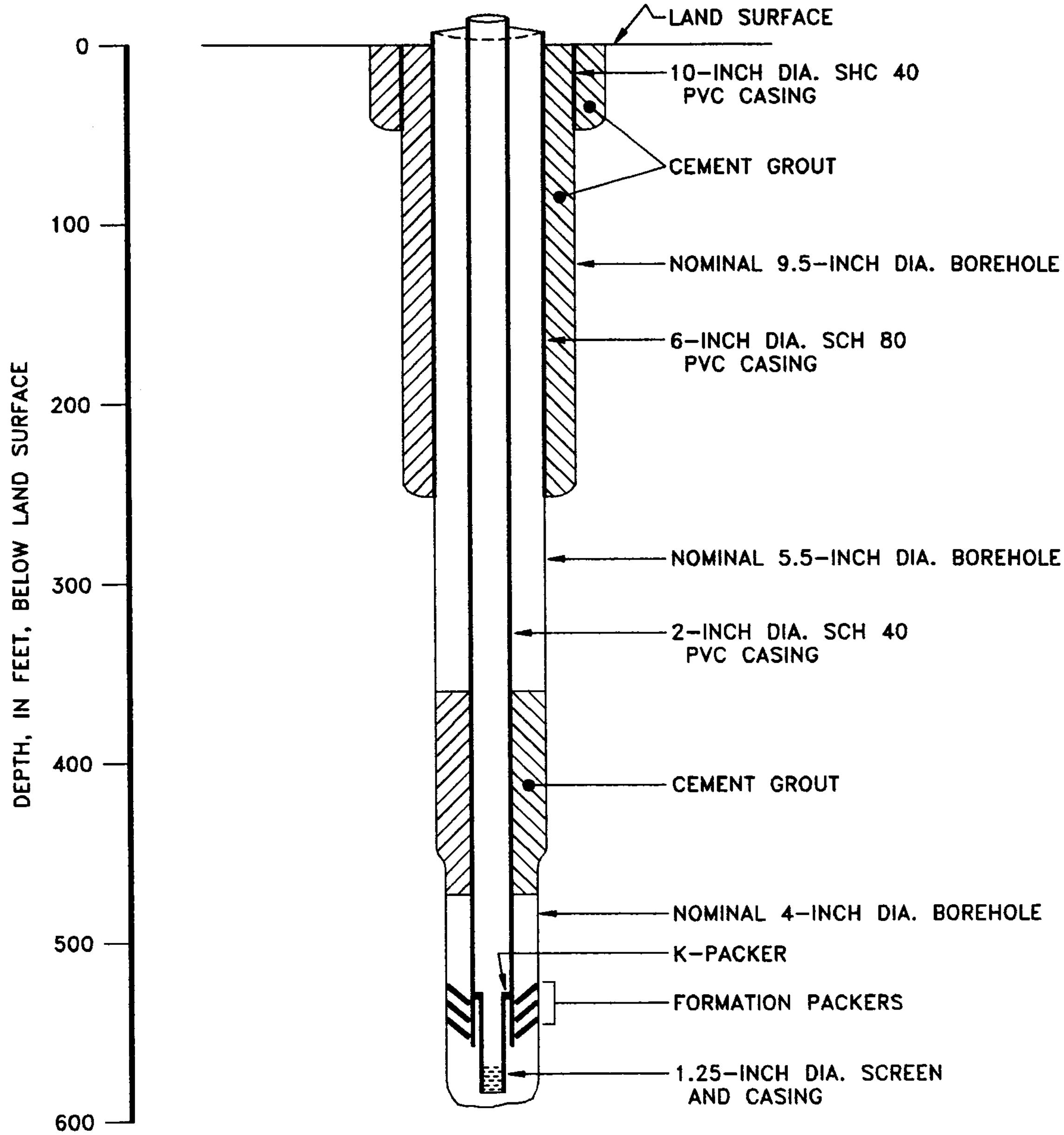
APPENDICES

TEST WELL DIAGRAMS

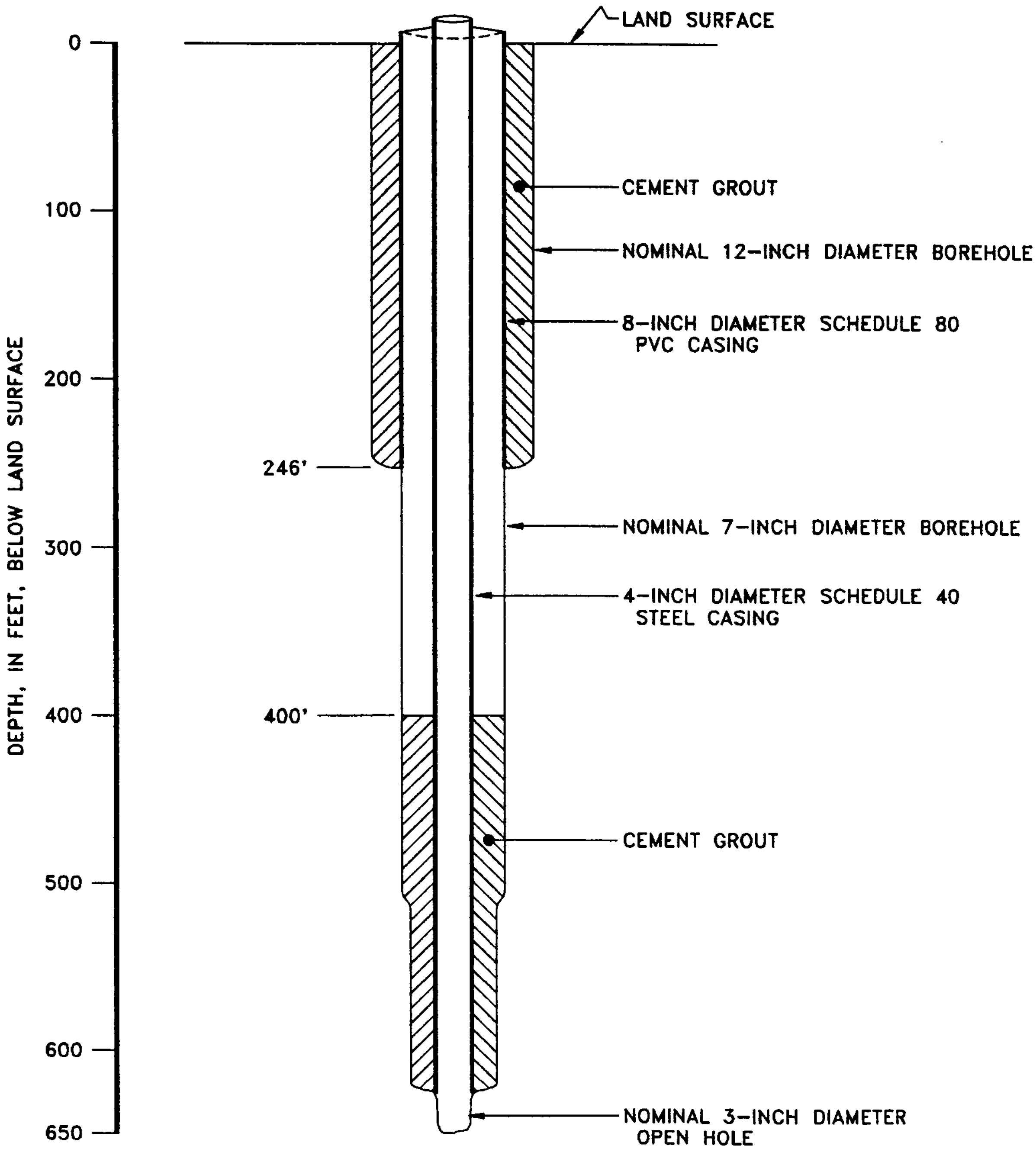
CAPE HATTERAS WATER ASSOCIATION REVERSE OSMOSIS TEST WELL TW-1



MISSIMER INTERNATIONAL	Pr Name: CAPE HATTERAS R.O. TEST WELL		Groundwater and Environmental Services
	Pr No. FH4-088	Date: 05/11/95	
	DWG No. FH4088W1.DWG	Rev.No. 2	

SCHEMATIC DIAGRAM SHOWING THE FINAL CONSTRUCTION DETAILS OF THE CAPE HATTERAS WATER ASSOCIATION REVERSE OSMOSIS TEST WELL TW-1.

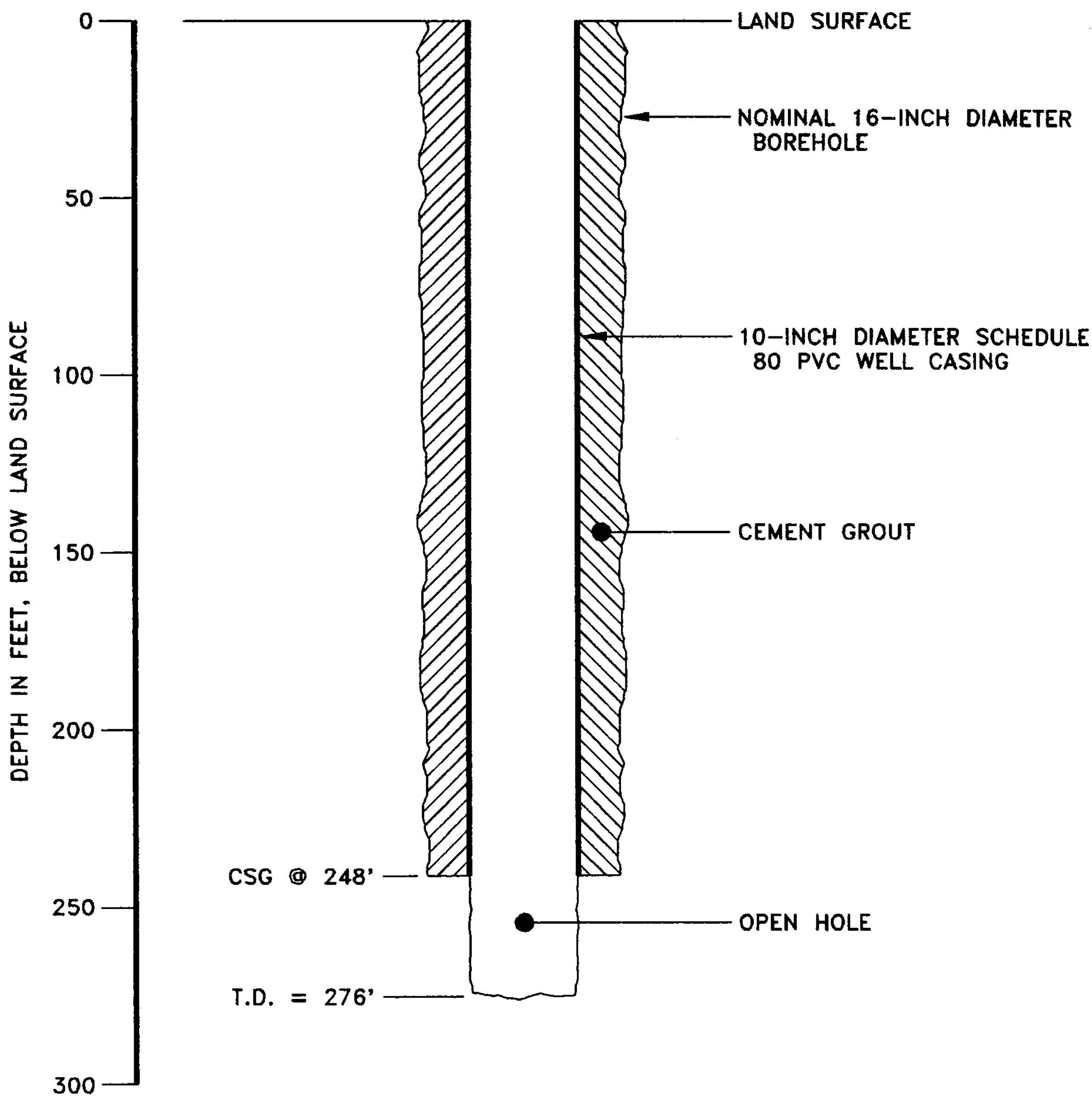
CAPE HATTERAS WATER ASSOCIATION REVERSE OSMOSIS TEST WELL TW-2



MISSIMER INTERNATIONAL	Pr Name: CAPE HATTERAS R.O. TEST WELL		Groundwater and Environmental Services
	Pr No. FH4-088	Date: 08/18/95	
	DWG No. FH4088W2.DWG	Rev.No. 3	

SCHEMATIC DIAGRAM SHOWING THE FINAL CONSTRUCTION DETAILS OF THE CAPE HATTERAS WATER ASSOCIATION REVERSE OSMOSIS TEST WELL TW-2.

CAPE HATTERAS WATER ASSOCIATION
BRACKISH WATER TEST WELL TW-3



MISSIMER INTERNATIONAL	Pr Name: CAPE HATTERAS	Groundwater and Environmental Services
	Pr No. FH4-088 Date: 08/18/95	
	DWG No. FH4088T3.DWG Rev.No. 2	

SCHEMATIC DIAGRAM SHOWING THE CONSTRUCTION DETAILS OF THE CAPE HATTERAS WATER ASSOCIATION BRACKISH WATER TEST WELL TW-3.

GEOLOGIST'S LOGS

GEOLOGIST'S LOG OF CAPE HATTERAS WATER ASSOCIATION REVERSE OSMOSIS TEST WELL TW-1

Depth (feet)	Description
0-45	No sample. Driller reports mix of fine to coarse grained sand and shell with clayey sand at the bottom of the interval.
45-50	Shell, multicolored, interbedded with sand. Sand is quartz, medium to coarse, subrounded, with some pebble sizes.
50-60	Sand, quartz, grayish-black (N2), very fine to coarse, poorly sorted, subrounded, abundant shell, black (N1), good apparent permeability.
60-82	Sand and shell as above.
82-89	Shell, grayish-black (N2), interbedded with fine sand and sandy clay, medium gray (N5).
89-99	Shell as above with less clay.
99-110	Clay, dark gray (N3), sandy, fine medium gray (N5) sand interbedded, abundant shell.
110-120	Shell, very pale orange (10 YR 8/2), interbedded with fine sand and occasional medium gray (N5) clay.
120-135	Clay, medium dark gray (N4), interbedded with fine sand and shell, very pale orange (10 YR 8/2), low apparent permeability.
135-150	Clay, medium dark gray (N4), sandy, common shell and fine sand interbedded, low permeability.
150-160	Clay, as above.
160-175	Clay, medium gray (N5), sandy, soft, common shell.
175-196	Clay, medium gray (N5), soft, sticky, minor shell fragments, minor fine sand, finely phosphatic.
196-215	Shell, multicolored, minor coarse sand, minor medium gray (N5) clay interbedded.
215-223	Shell, multicolored, interbedded with common medium gray (N5) clay, and fine to coarse grained quartz sand.
223-238	Clay, medium gray (N5), soft, sticky, common shell interbedded.
238-250	Limestone, medium dark gray (N4) to medium gray (N5), soft to medium hard, shell casts and molds, trace white lime mud, minor shell.
250-275	Limestone, medium gray (N5), soft to medium hard, casts and molds, common shell, high permeability. Interbedded with soft, medium dark gray (N4), friable sandstone. Severe loss of circulation zones encountered at 255 feet and 265 feet.

GEOLOGIST'S LOG OF CAPE HATTERAS WATER ASSOCIATION
REVERSE OSMOSIS TEST WELL TW-1
-CONTINUED-

Depth (feet)	Description
275-285	Limestone, medium dark gray (N4), sandy, soft to medium hard, friable, finely phosphatic, common shell fragments. Good apparent permeability.
285-294	Limestone, yellowish-gray (5 Y 8/1), sandy, medium hard, moderately well indurated, common shell fragments.
294-303	Limestone, yellowish-gray (5 Y 8/1), sandy, medium hard, moderately well indurated, casts and molds, common shell fragments, good apparent permeability.
303-313	Limestone, yellowish-gray (5 Y 8/1), soft, friable, clayey, poorly indurated, occasional shell fragments, fast rate of penetration, low to medium apparent permeability.
313-325	Limestone, as above.
325-334	Limestone, medium gray (N5), soft to medium hard, friable, poorly to moderately indurated, finely phosphatic, abundant shell fragments, minor white carbonate mud.
334-339	Limestone, as above.
339-345	Clay, brownish-gray (5 YR 4/1), soft, cohesive, carbonate, common shell and limestone fragments, low apparent permeability.
345-355	Sandy limestone, yellowish-gray (5 Y 8/1), soft to medium hard, poorly to moderately indurated, friable, minor shell. Low to medium apparent permeability.
355-366	Limestone, as above with minor clay interbedded.
366-376	Limestone, medium light gray (N6), soft to medium hard, poorly to moderately indurated, friable, abundant shell fragments, medium apparent permeability.
376-400	Limestone, yellowish-gray (5 Y 8/1), soft to medium hard, friable, occasional shell fragments, minor clay interbedded. Low to medium apparent permeability.
400-405	Limestone and clay, as above.
405-415	Clay, grayish-olive green (5 GY 3/2), soft, cohesive, common limestone and shell fragments.
415-421	Shell, multicolored, common limestone fragments, minor clay and sand interbedded.
421-442	Shell, multicolored, interbedded with coarse, rounded quartz sand. Formation taking fluid during drilling, medium to high apparent permeability.
442-462	Clay, grayish-olive green (5 GY 3/2), soft, sticky, minor shell and limestone fragments, low permeability.

GEOLOGIST'S LOG OF CAPE HATTERAS WATER ASSOCIATION REVERSE OSMOSIS TEST WELL TW-1 -CONTINUED-

Depth (feet)	Description
462-525	Clay, grayish-olive green (5 GY 3/2), soft, sandy, carbonate, minor shell interbedded, low permeability.
525-546	Clay, dusky yellowish-brown, soft, sandy, cohesive, trace shell. Sand is very fine grained.
546-557	Clay, as above.
557-567	Sandstone, light olive-gray (5 Y 5/2), soft to medium hard, friable, poorly to moderately indurated, finely phosphatic, shell lense at the top of the unit. Minor casts and molds, minor shell interbedded with sandstone, medium apparent permeability.
567-588	Sandstone, light gray (N7) to light brownish-gray (5 YR 6/1), soft to hard, friable, finely phosphatic (salt & pepper effect), minor shell fragments, minor casts and molds.

GEOLOGIST'S LOG OF CAPE HATTERAS WATER ASSOCIATION REVERSE OSMOSIS TEST WELL TW-2

Depth (feet)	Description
0-7	Sand, medium gray (N5), fine grained, quartz, well sorted, subrounded.
7-20	Sand and gravel, medium gray (N5), and multi-colored, fine to gravel sized, quartz, poorly sorted, subangular to well rounded, 20-25% shell fragments.
20-30	Sand, gravel and shell, as above.
30-40	Sand and shell, medium gray (N5), and greenish-gray (5 GY 6/1), fine to coarse grained, quartz and assorted minerals, poorly sorted, minor interbedded clay.
40-50	Sand and shell, as above.
50-60	Sand, medium gray (N5), fine to coarse grained, quartz, minor shell and echinoid fragments, very minor interbedded clay.
60-75	Sand as above, higher % shell fragments.
75-100	Shell, interbedded with fine to coarse quartz sand, multi-colored, minor interbedded clay.
100-107	Shell, as above.
107-128	Sand, medium gray (N5), to light olive-gray (5 Y 6/1), fine grained, quartz, minor shell.
128-142	Clay, greenish-gray (5 GY 5/1), soft, semi-cohesive, interbedded with fine sand and shell, low apparent permeability.
142-175	Clay, light olive-gray (5 Y 6/1), soft, slightly cohesive, interbedded with fine sand and shell, slightly phosphatic, low apparent permeability.
175-195	Clay and interbedded shell, light olive-gray (5 Y 6/1), soft, minor fine sized sand, low apparent permeability.
195-220	Interbedded clay, shell and sand, as above, gastropods abundant from 215-220 feet.
220-244	Interbedded clay, shell and sand, as above, finely phosphatic.
244-255	Limestone, medium gray (N5) to light olive-gray (5 Y 6/1), medium hard to soft, packstone, some friable pieces, vuggy, moldic, common shell fragments, good apparent permeability, minor fine phosphate, minor quartz sand.
255-264	Limestone, as above, but a little harder.
264-275	Limestone, as above, common casts and molds, hard, minor lost circulation zone.
275-285	Limestone, as above, severe lost circulation zone at 280 feet.

GEOLOGIST'S LOG OF CAPE HATTERAS WATER ASSOCIATION REVERSE OSMOSIS TEST WELL TW-2 -CONTINUED-

285-300	Limestone, medium gray (N5) and yellowish-gray (5 GY 8/1), packstone, hard to soft, vuggy, moldic, minor fine sand, common bivalves and gastropods, good apparent permeability.
300-315	Limestone, yellowish-gray (5 Y 7/1), packstone, soft, friable, moldic, common shells, slightly phosphatic, minor clay (white lime mud).
315-340	Limestone, as above, but harder.
340-368	Limestone, as above.
368-385	Limestone, as above.
385-406	Limestone, light to very light gray (N) and yellowish-gray (5 Y 6/2), hard to medium hard, moldic, vuggy, common shell fragments, minor fine sand, good apparent permeability, minor lost circulation.
406-410	Limestone, yellowish-gray (5 Y 7/2), as above, interbedded sandy clay.
410-425	Clay, light olive-gray (5 Y 5/2), soft, semi-cohesive, abundant fine sand and silt, minor shell, low apparent permeability.
425-440	Clay, as above, common shell and limestone fragments.
440-450	Shell, multi-colored, common limestone fragments, minor sand and clay, interbedded.
450-475	Sandy clay, light olive-gray (5 Y 5/2), very soft, minor shell, minor fine phosphate, low apparent permeability.
475-498	Sandy clay, as above.
498-523	Clay, light olive-gray (5 Y 4/2), soft, semi-cohesive, sandy, finely phosphatic, minor shell.
523-545	Clay, as above.
545-565	Clay, light olive-gray to yellowish-gray (5 Y 7/2), soft, semi-cohesive, sandy, finely phosphatic, minor shell, low permeability.
565-583	Sand, light olive-gray, fine grained, quartz, minor shell and clay, finely phosphatic, interbedded sandstone, as below.
583-598	Sandstone, light olive-gray (5 Y 6/1) to yellowish-gray (5 Y 8/1), fine to medium grained quartz, soft to hard, some friable pieces, minor clay and shell, finely phosphatic, medium apparent permeability.
598-623	Sandstone, as above, minor casts and molds.
623-635	Sandstone, as above.

635-650	Sandstone, light olive-gray (5 Y 6/1) to yellowish-gray (5 Y 8/1), fine to medium grained, soft to medium hard, loosely consolidated, finely phosphatic, minor clay and shell, medium permeability.

GEOLOGIST'S LOG OF CAPE HATTERAS WATER ASSOCIATION REVERSE OSMOSIS TEST WELL TW-3

Depth (feet)	Description
0-18	No samples collected. Drillers describe fine to medium grained sand with some shell present.
18-48	Sand and shell, medium gray (N5) to multi-colored, fine to coarse grained, quartz, poorly sorted, subrounded, minor black sand.
48-60	Sand and shell, as above.
60-74	Sand and shell, as above, minor gravel sized quartz.
74-95	Sand and shell, medium gray (N5) sand, shell is grayish-black (N2), fine grained, quartz, minor phosphate.
95-106	Clay, greenish-gray (5 GY 5/1), soft, semi-cohesive, low apparent permeability and porosity, shells and fine sand common.
106-112	Sandy clay, greenish-gray (5 GY 5/1), soft, semi-cohesive, low apparent permeability, very fossiliferous (gastropods, bivalves).
112-124	Clay, as above, less sand.
124-145	Clay with interbedded sand and shell, as above.
145-175	Clay, light olive-gray (5 Y 5/1) to medium gray (N5), soft, cohesive, low apparent permeability, finely phosphatic, minor interbedded sand and shell (common gastropods).
175-218	Clay, as above.
218-245	Clay and interbedded shell, light olive-gray (5 Y 6/1), soft, cohesive, low permeability, finely phosphatic, common gastropod and echinoid fragments, minor sand.
245-260	Limestone, medium gray (N5), to yellowish-gray (5 Y 8/1), medium hard to soft, some friable pieces, packstone, moldic and vuggy, good apparent permeability and porosity, common shell and fine sand, minor phosphate.
260-276	Limestone, as above, lost circulation zone from 260 to 265 and 270 to 276.

DARE COUNTY HATTERAS WATER SYSTEM
GEOLOGIST'S LOG OF REVERSE OSMOSIS TEST WELL R.O. TW-4

Depth (feet)	Description
0-15	Sand, quartz, yellowish-gray (5Y 8/1) to medium gray (N5), fine to coarse grained, poorly sorted, subangular, common shell, common organics.
15-25	Sand, quartz, medium dark gray (N4), fine to coarse grained, poorly sorted, subangular, common shell fragments.
25-30	Sand, quartz, multicolored, fine to pebble sizes, poorly sorted, abundant shell fragments.
30-37	Sand, quartz, medium gray (N5), fine, well sorted, occasional shell, minor gray clay interbedded.
37-45	Sand, light gray (N7), fine to medium grained, subangular, moderately well sorted, abundant shell (bivalves, barnacles, oysters), minor dark gray clay interbedded.
45-60	Sand, quartz, grayish-black (N2), fine to coarse grained, poorly sorted, subrounded, abundant black shell fragments (N1).
60-80	Shell, grayish-black (N2), abundant fine to medium grained sand interbedded, trace gray clay.
80-90	Shell, grayish-black (N2), common fine to medium grained sand interbedded, common medium gray (N5) sandy clay.
90-105	Clay, light olive-gray (5Y 6/1) to medium gray (N5), sandy, soft, sticky, common shell interbedded.
105-135	Clay, greenish-gray (5GY 5/1), soft, finely phosphatic, common shell, minor sand.
135-150	Clay, greenish-gray (5GY 5/1), sandy, soft, occasional shell fragments.
150-165	Clay, light olive-gray (5Y 5/1) to medium gray (N5), soft, sandy, common shell fragments.
165-180	Clay, light olive-gray (5Y 5/1), soft, sandy, finely phosphatic, common shell fragments.
180-195	Clay, greenish-gray (5GY 6/1), stiff, sticky, minor shell interbedded.
195-210	Shell, multicolored, interbedded with medium gray (N5) sandy clay.
210-225	Shell, multicolored, interbedded with medium gray (N5) finely phosphatic clay. Hard lense @ 213 feet.
225-241	Clay, medium gray (N5), soft, sticky, phosphatic, common shell lenses interbedded.
241-255	Limestone, medium dark gray (N4), medium hard, casts and molds, moderate to good apparent permeability and porosity, occasional shell fragments.
255-278	Limestone, as above. Loss of circulation zone encountered @ 265 feet.
	TD = 278 feet below land surface.

DARE COUNTY HATTERAS WATER SYSTEM
GEOLOGIST'S LOG OF REVERSE OSMOSIS TEST WELL R.O. TW-5

Depth (feet)	Description
0-14	Sand, quartz, medium gray (N5) to yellowish gray (5Y 8/1), fine, well sorted, subangular, minor organics.
14-40	Sand, medium gray (N5), fine to coarse grained, poorly sorted, subangular to rounded, common shell fragments.
40-52	Clay, dark gray (N3), soft, sticky, sandy, common shell.
52-58	Sand, brownish-gray (5YR 4/1), coarse grained, subrounded, minor fine sand and shell interbedded.
58-74	Shell, dark gray (N3) to black (N1), common sand interbedded.
74-89	Sand, medium gray (N5), fine to coarse grained, poorly sorted, abundant dark shell interbedded, minor gray clay.
89-104	Shell, multicolored - mostly medium gray (N5), common fine to medium grained sand interbedded, common medium gray (N5) sandy clay interbedded.
104-119	Clay, greenish-gray (5GY 5/1), sandy, soft, abundant shell interbedded.
119-134	Shell, very pale orange (10YR 8/2), mostly bivalves, common medium gray (N5) clay, minor fine sand.
134-149	Clay, medium dark gray (N4), sandy, interbedded with abundant shell (bivalves), common fine to coarse grained sand.
149-164	Clay, as above. Interbedded with sand and shell.
164-194	Clay, medium gray (N5), sandy, soft, sticky, abundant shell.
194-215	Clay, light olive-gray (5Y 5/1) to medium gray (N5), soft, sticky, sandy, common shell fragments.
215-224	Shell, multicolored, bivalves and gastropods, minor sand and medium gray (N5) clay interbedded.
224-239	Shell, multicolored, bivalves and gastropods, abundant medium grained sand, minor medium gray (N5) clay. Hard lense @ 226 feet.
239-250	Clay, medium gray (N5), soft, sandy, finely phosphatic, abundant shell interbedded.
250-257	Limestone, medium dark gray (N4), medium hard, moderately well indurated, moderate to good apparent permeability and porosity, occasional shell fragments.
257-284	Limestone, medium dark gray (N4), soft to medium hard, shell casts, moldic, vuggy, high porosity and permeability, common shell fragments. Loss of circulation zone encountered @ 268 feet.
	TD = 284 feet below land surface

GEOLOGIST'S LOG
WELL TW-6

Depth	Geologic Description
0-1	Sand (100%), quartz, feldspar, and dark minerals, dark yellowish brown (10YR 4/2), mud to fine sand size, poorly sorted. Organics including roots and some gravel (most likely fill material).
1-7	Sand (100%), dark yellowish orange (10YR 6/6), quartz with black (N1) minerals and minor feldspar, very fine sand, well sorted.
7-18	No sample collected. Most likely sand as above. Formation is very porous, lost circulation from 14-18 ft bls.
18-36 to	Interbedded shell and sand. Shells, multi-colored bivalves. Sand, quartz, light gray (N7) to greenish gray (5GY 6/1), very fine to medium grained, moderately poorly sorted.
36-45	Interbedded shell and sand (as above with a greater percentage of sand.) Shells, multi-colored bivalves. Sand, quartz, medium light gray (N6) to light gray (N7) to greenish gray (5GY 6/1), very fine to medium grained, moderately to poorly sorted.
45-66	Interbedded shell, sand, and clay. Shell, multi-colored bivalves, gastropods, and sand dollars. Sand, quartz, medium light gray (N6) to light gray (N7) to greenish gray (5GY 6/1), mud to granule size, poorly sorted. Clay (5%), medium light gray (N6), soft.
66-74.5	Interbedded sand and shells. Sand, quartz and dark minerals. Shells, black (N1), bivalves and echinoid spines.
74.5-104	Interbedded sand, shells, and clay. Sand, quartz and dark minerals, very fine to medium grained, moderately sorted. Shells, black (N1), bivalves and echinoid spines. Clay (5%), dark greenish gray (5GY 4/1), soft.
104-119.5	Interbedded sand, shell, and clay. Shells, bivalves, many are black (N1) but also multi-colored. Sand, quartz and dark minerals, very fine to medium grained, moderately sorted. Clay, medium bluish gray (5B 5/1), soft.
119.5-136	Interbedded sand, shell, and clay. Sand, quartz and minor dark minerals, very fine to fine grained, well sorted. Clay, dark greenish gray (5GY 4/1), soft. Shells, many are black also multi-colored, bivalves, gastropods, and sand dollars.

Continued:

GEOLOGIST'S LOG
WELL TW-6

Depth	Geologic Description
136-144	Shells, many are black also multi-colored, bivalves, gastropods, and sand dollars. Sand, quartz and minor dark minerals, very fine to fine grained, well sorted.
144-177	Interbedded shells, sand, and clay. Shells (45%), many are black also multi-colored, bivalves, gastropods, and sand dollars. Clay (45%), dark greenish gray (5GY 4/1), soft. Sand (10%), quartz, very fine to fine grained.
177-211	Interbedded shells and sandy clay. Shells (60%), many are black but they are also multi-colored, bivalves, gastropods, echinoid spines, and sand dollars. Sandy clay (40%), dark greenish gray (5GY 4/1), soft, with very fine to fine-grained quartz sand with heavy dark minerals.
211-227	Same geologic description as 177-211 ft. Harder formation with more rig chatter. Slight loss of circulation.
227-241	Same as 177-211 ft.
241-261	Interbedded shells, sandy clay, and sand. Shells (55%), many are black but they are also multi-colored, bivalves, gastropods, echinoid spines, and sand dollars. Sandy clay (30%), dark greenish gray (5GY 4/1), soft, with very fine to fine-grained quartz sand and heavy dark minerals. Sand (15%), predominantly quartz, very fine to granule size, very poorly sorted, subrounded.
271-272.5	Interbedded sand, shells, and pebbles. Sand, quartz and other minerals, very fine to coarse-grained, poorly sorted, subrounded. Shells, multi-colored, bivalves. Pebbles (15%), quartz and unidentified rocks, subrounded to rounded.
272.5-313	Limestone (100%), wackestone/packstone, medium gray (N5) to medium dark gray (N4), moderate to high (moldic) macroporosity, soft, numerous white bivalve shells.
313-319	No sample collected but most likely limestone as 272.5-313 ft.

***Note: Lost circulation at 316 feet below land surface

GEOLOGIST'S LOG
WELL TW-7

Depth	Geologic Description
0-5	Sand (100%), quartz, feldspar, heavy minerals, black (N1), light grey (N7), and white (N9), very fine to medium grained, subangular, moderately to poorly sorted. Organic debris.
5-15	Most likely sand as above but no sample collected.
15-31	Interbedded sand and shell. Sand, quartz and unidentified rock, minor amounts of fine-grained sand but mostly granule size, subrounded to rounded, moderately sorted. Shell, multi-colored bivalves.
31-44	Interbedded shell and sand. Shells include clams, sand dollars, and gastropods, more shells than 15-31 ft. Sand, quartz, unidentified rock, and heavy minerals, very fine to fine-grained and granule size sand, poorly sorted.
44-60	Interbedded shell, sand, and clay. Shells (85%), multi-colored bivalves. Sand (10%), quartz and unidentified rock, very fine and granule size, poorly sorted, subrounded to rounded. Clay (5%), dark greenish gray (5GY 4/1), soft.
60-75	Interbedded shell, sand, and clay. Shells, (85%), mostly black and gray, but also multi-colored bivalves. Sand (10%), quartz and unidentified rock, very fine to fine and granule size, subrounded. Clay (5%), dark greenish gray (5GY 4/1), soft.
75-89	Interbedded shell, sand, and clay. Shells, (80%), mostly black and gray, but also multi-colored bivalves. Sand (10%), quartz and unidentified rock, very fine to fine and granule size, subrounded. Clay (10%), dark greenish gray (5GY 4/1), soft.
89-94	Interbedded shell, clay, and sand. Shells (80%), bivalves and gastropods, mostly black and gray. Clay (15%), dark greenish gray (5GY 4/1), soft. Sand (5%), quartz, very fine to fine-grained and granule size, subrounded, poorly sorted.
94-104	Interbedded shell and clay. Shells, (80%), mostly bivalves, multi-colored. Clay (20%), dark greenish gray (5GY 4/1), soft.
104-119	Interbedded shell and clay. Shells (55%), gastropods and bivalves, many are brown but also multi-colored. Clay (45%), greenish gray (5G 6/1) to dark greenish gray (5GY 4/1).

Continued:

GEOLOGIST'S LOG
WELL TW-7

Depth	Geologic Description
119-136	Interbedded shell and clay. Shells, (75%), bivalves, echinoid spines, and barnacles. Clay (25%), greenish gray (5G 6/1) to dark greenish gray (5GY 4/1).
136-151	Interbedded clay and shell. Clay (85%), dark greenish gray (5GY 4/1), soft. Shells (15%), bivalves and echinoid spines.
151-164	Interbedded clay and shell. Clay (75%), dark greenish gray (5GY 4/1), soft. Shells (25%), bivalves and gastropods.
164-194	Interbedded clay and shell. Clay (50%), dark greenish gray (5GY 4/1) to greenish gray (5G 4/1), soft. Shells (50%), multi-colored, bivalves and minor gastropods.
194-212	Interbedded clay and shell. Clay (70%), dark greenish gray (5GY 4/1) to greenish gray (5G 4/1), soft. Shells (30%), multi-colored, bivalves and minor gastropods.
212-223	Interbedded shell, clay, and sand. Shells (40%), multi-colored, bivalves and gastropods. Clay (35%), dark greenish gray (5GY 4/1), soft. Sand, quartz, very fine to medium grained, subrounded, poorly sorted.
223-258	Interbedded sand and shells. Sand (90%), olive gray (5Y 4/1), quartz and heavy minerals, very fine to medium grained, moderately sorted. Shells (10%), bivalves.
258-269	Interbedded sand and shells. Sand (50%), dark greenish gray (5GY 4/1), quartz and unidentified rock, fine to coarse grained, subrounded to rounded. Shells (50%), bivalves and gastropods.
269-282	Sand, quartz and heavy minerals, very fine to coarse grained, subrounded, poorly sorted. Shell, mostly white colored, bivalves. Limestone (10%), wackestone, medium gray (N5), moderate macroporosity.
282-288	Sandy limestone (90%), wackestone, medium gray (N5), with 10% quartz grains, subrounded, moderate macroporosity. Shells (10%), multi-colored bivalves.
288-296	Limestone (75%), wackestone, medium gray (N5), moderate (moldic) macroporosity, moderately hard. Shells and shell fragments (15%), multi-colored bivalves, some have rounded edges. Pebbles (10%) quartz and unidentified rocks, rounded.

Continued:

GEOLOGIST'S LOG
WELL TW-7

Depth	Geologic Description
296-317	Limestone (90%), wackestone, medium gray (N5), moderate (moldic) macroporosity, moderately hard. Shells and shell fragments (10%), multi-colored bivalves, some have rounded edges.
317-326	***Lost circulation at 317 feet below land surface so did not recover cuttings from this interval.

GEOLOGIST'S LOG
WELL TW-8

Depth	Geologic Description
0-5	Sand, quartz, minor feldspar, and dark minerals, pale yellowish brown (10YR 6/2), very fine to medium grained, moderately sorted, and organic debris including roots.
5-11	Sand, quartz, minor feldspar, and dark minerals, pale yellowish brown (10YR 6/2), very fine grained to granule size, poorly sorted, subrounded.
11-31	Interbedded shells and sand. Shells (50%), multi-colored bivalves and minor echinoid spines. Sand (50%), light olive gray (5Y 5/2), quartz, minor feldspar, and dark minerals, very fine to medium grained, moderately sorted.
31-45	Interbedded sand and shell. Sand (60%), very fine grained to granule size, poorly sorted, subrounded. Shells (40%), multi-colored bivalves.
45-68	Sand, light olive gray (5Y 6/1), quartz and dark minerals, very fine to fine grained, well sorted, with minor bivalve shells.
68-90	Interbedded sand and shell. Sand (50%), quartz and dark minerals, very fine grained to granule size, subrounded, medium dark gray (N4) to dark gray (N3). Shells (50%), bivalves, black (N1) and multi-colored.
90-112	Interbedded shell and sand. Shells (70%), most are black (N1) bivalves. Sand (30%), mostly quartz, very fine to very coarse-grained, poorly sorted, subrounded.
112-119	Interbedded shells, sand, and clay. Shells (90%), multi-colored bivalves, gastropods, and echinoid spines. Sand (5%), quartz, very fine to medium grained, moderately sorted. Clay (5%), dark greenish gray (5GY 4/1), soft.
119-134	No sample collected. Most likely interbedded sand, shell, and clay.
134-164	Interbedded shell and clay. Shells (50%), black and multi-colored bivalves and razor clams. Clay (50%), dark greenish gray (5GY 4/1) to medium bluish gray (5B 5/1), soft.
164-179	Interbedded sand and shell. Sand (60%), quartz and minor dark minerals, very fine to coarse-grained, poorly sorted, subrounded. Shells (40%), multi-colored bivalves.

Continued:

GEOLOGIST'S LOG
WELL TW-8

Depth	Geologic Description
179-194	Interbedded shell, sand, and clay. Shells (50%), multi-colored bivalves, razor clams, and limpets (?). Sand (45%), quartz, very fine to coarse-grained, subrounded, poorly sorted. Sandy clay (5%), dark greenish gray (5GY 4/1), soft.
194-224	Interbedded shell, sand, and clay. Shells (60%) multi-colored bivalves, gastropods, and razor clams. Sand, quartz, very fine to coarse-grained, poorly sorted, subrounded. Sandy clay (15%), dark greenish gray (5GY 4/1), soft.
224-243	Interbedded clay and shell. Clay (50%), dark greenish gray (5GY 4/1), soft. Shells (50%), multi-colored bivalves.
243-255	Limestone, medium gray (N5), wackestone, moderate (moldic) macroporosity, hard.
255-260	Limestone, wackestone, very light grey (N8) to medium dark grey (N4), moderate (moldic) macroporosity, hard.
260-270	Limestone, wackestone, medium dark grey (N4), moderate (moldic) macroporosity, with bivalves and bivalve casts, moderately hard.
270-278	Limestone, wackestone, medium light grey (N6) to medium dark grey (N4), moderate (moldic) macroporosity with bivalves and bivalve casts, moderately hard.
278-300	Limestone (85%), wackestone, yellowish gray (5Y 8/1) to medium grey (N5), high (moldic) macroporosity with bivalves, bivalve molds, and casts, moderately hard. Shells (15%), bivalves.
300-329.5	Limestone, wackestone, yellowish gray (5Y 8/1) to medium grey (N5), high (moldic) macroporosity with bivalves, bivalve molds, and casts, moderately hard.

***Note: Did not lose complete circulation while drilling this well. Did lose slight circulation at 320 feet below land surface.

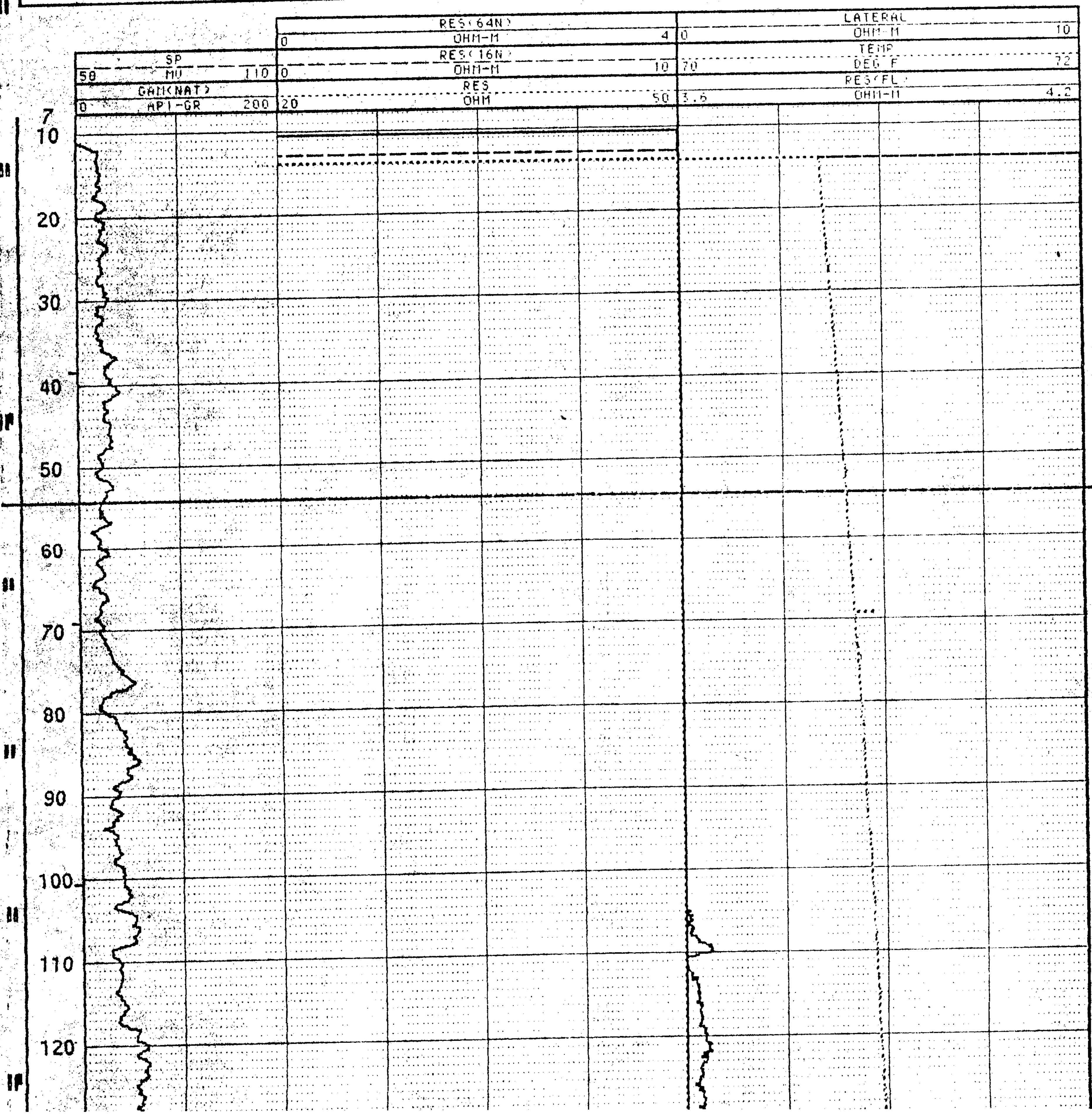
GEOPHYSICAL LOGS
WELL R.O. TW-1

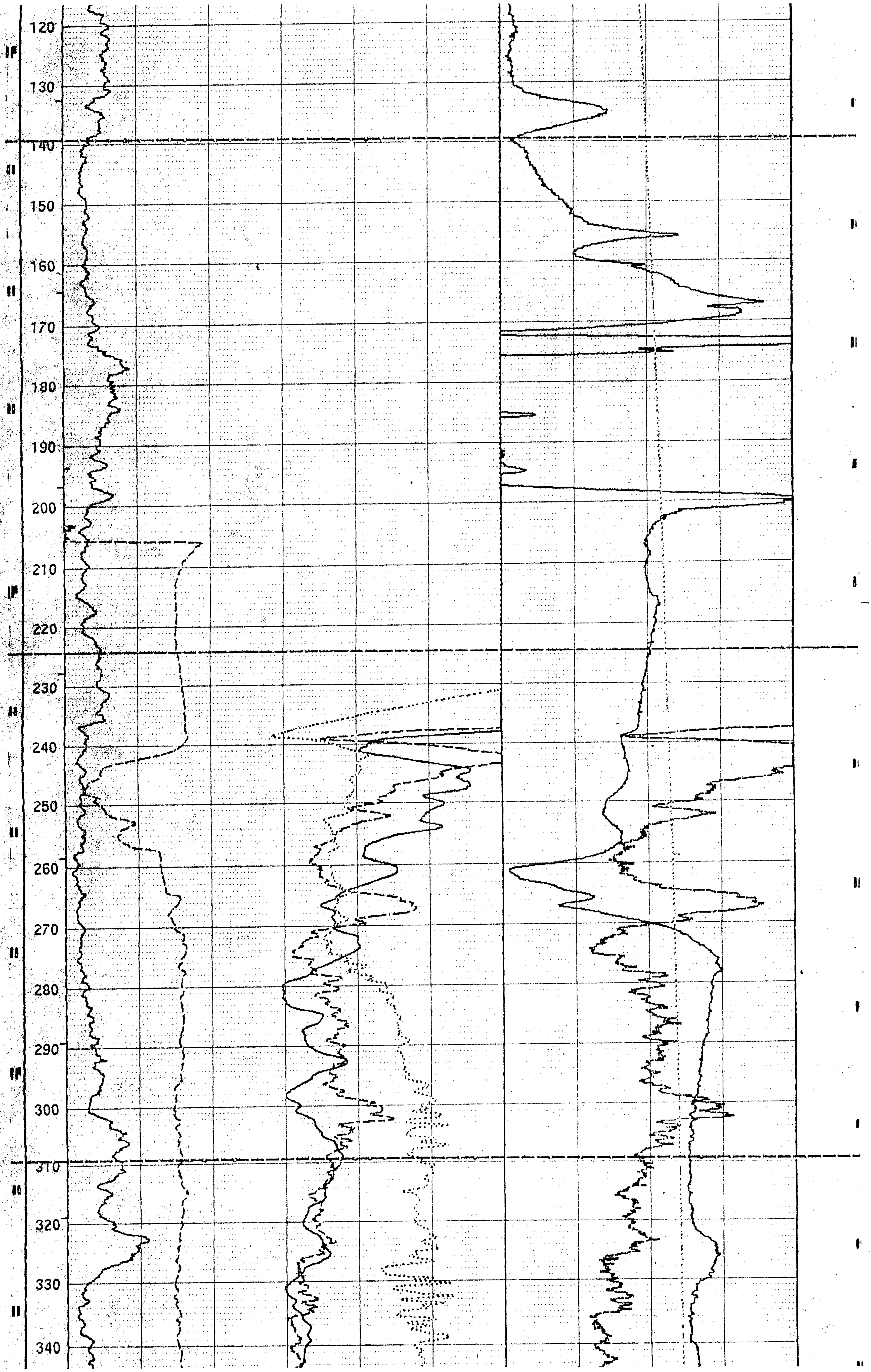
STATE OF NORTH CAROLINA
DEPARTMENT OF ENVIRONMENT HEALTH
AND NATURAL RESOURCES
DIVISION OF ENVIRONMENTAL MGMT.
GROUNDWATER SECTION
512 NORTH SALISBURY STREET
ARCHADALE BLDG., ROOM 826
P.O. BOX 27687, RALEIGH NC 27611

RO - Test Well # 1

COMPANY	: Cape Hatteras Water Associatin			OTHER SERVICES: - -	
WELL	: RO - Test Well # 1				
LOCATION/FIELD	: North Frisco - Ocean Side				
COUNTY	: Dare				
STATE	: NC			RANGE	:
SECTION	:	TOWNSHIP	:		
DATE	: 04/21/95	PERMANENT DATUM	: msl	ELEVATIONS	
DEPTH DRILLER	: 585	ELEV. PERM. DATUM	: 0.00	KB	:
LOG BOTTOM	: 588.40	LOG MEASURED FROM	: Ground	DF	:
LOG TOP	: 7.00	DRL MEASURED FROM	: -	GL	: 5
CASING DRILLER	: 240	LOGGING UNIT	: 9111		
CASING TYPE	: PVC	FIELD OFFICE	: CO		
CASING THICKNESS	: 80	RECORDED BY	: mike vaught		
BIT SIZE	: 4	BOREHOLE FLUID	: Ben	FILE	: ORIGINAL
MAGNETIC DECL.	:	RM	:	TYPE	: 9041A
MATRIX DENSITY	:	RM TEMPERATURE	:	LOG	: 9
FLUID DENSITY	: 9	MATRIX DELTA T	:	PLOT	: 9041A 0
NEUTRON MATRIX	:	FLUID DELTA T	:	THRESH	: 999999

REMARKS :
From Hwy 12 in North Frisco Take Water Assoc Rd on ocean side approx 100yd
Csg to 240, 5.5" hole to 462, then 4" hole to 585. lost circ @ 265 sleve drill
ALL SERVICES PROVIDED SUBJECT TO STANDARD TERMS AND CONDITIONS

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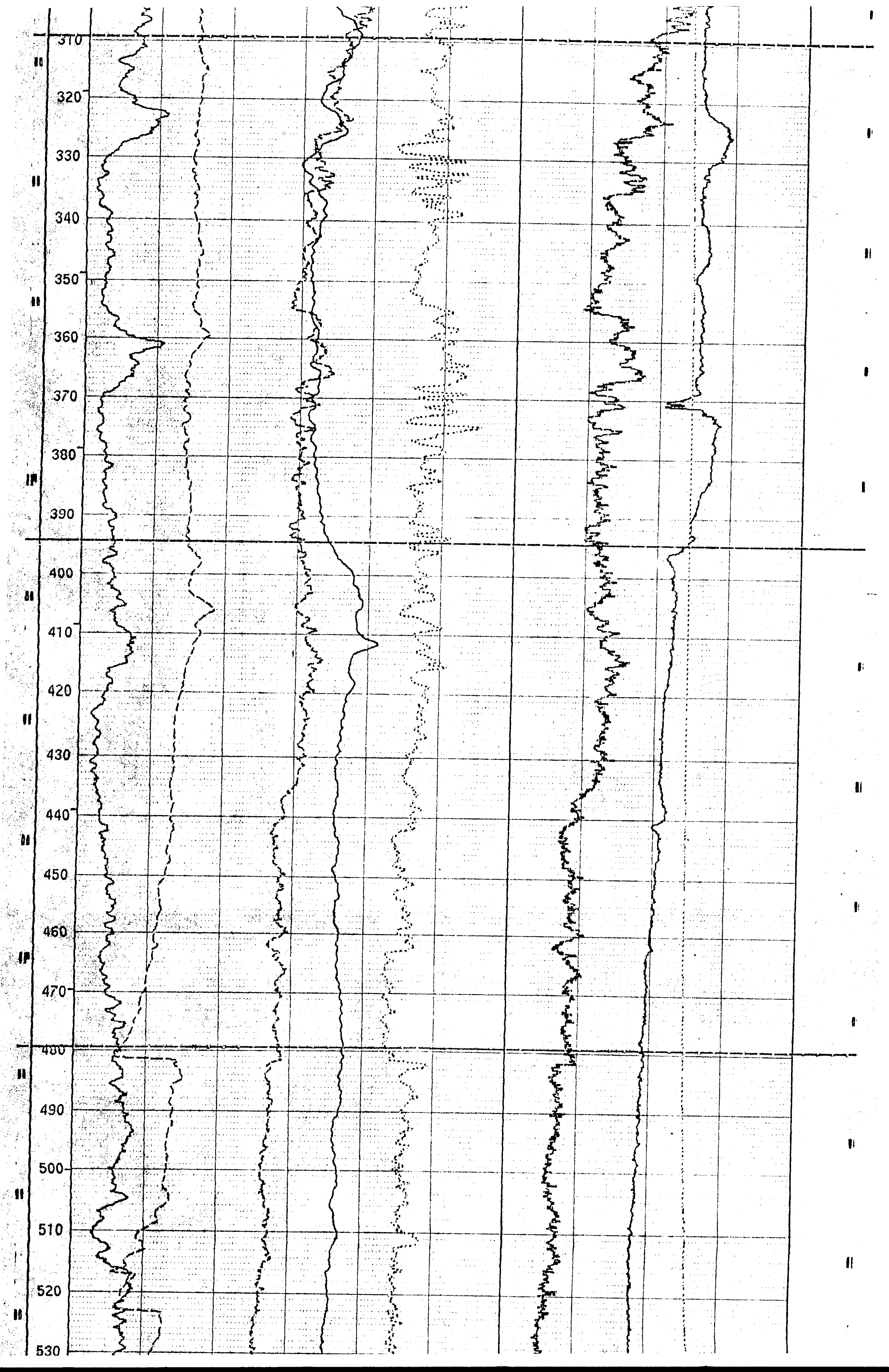
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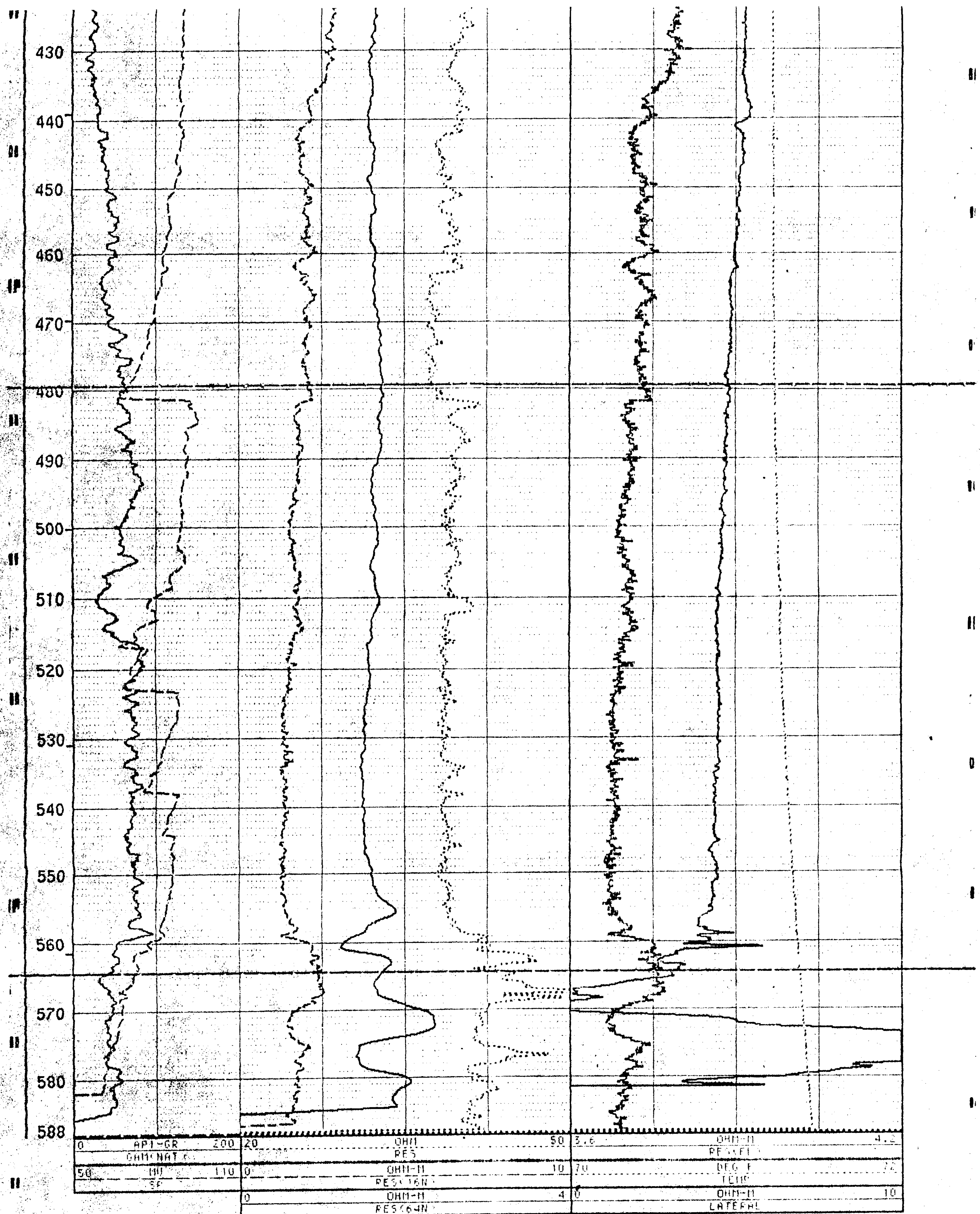


TOOL CALIBRATION   TOOL = 9041A   SERIAL NUMBER = 273

	CAL-DATE	CAL-TIME	SRCE	SENSOR	RESPONSE	STANDARD	
0	OCT05.90	11:03:44	0	GAM(NAT)	0.000 CPS	0.000	API-GR
1	OCT05.90	11:03:44	0	GAM(NAT)	0.000 CPS	0.000	API-GR
2	OCT05.90	11:03:44	0	RES(FL)	0.000 CPS	0.000	OHM-M
3	OCT05.90	11:03:44	0	RES(FL)	0.000 CPS	0.000	OHM-M
4	OCT05.90	11:03:44	0	SP	0.000 CPS	0.000	MV
5	OCT05.90	11:03:44	0	SP	0.000 CPS	0.000	MV
6	OCT05.90	11:03:44	0	RES(16N)	0.000 CPS	0.000	OHM-M
7	OCT05.90	11:03:44	0	RES(16N)	0.000 CPS	0.000	OHM-M
8	OCT05.90	11:03:44	0	RES(64N)	0.000 CPS	0.000	OHM-M
9	OCT05.90	11:03:44	0	RES(64N)	0.000 CPS	0.000	OHM-M
10	OCT05.90	11:03:44	0	TEMP	0.000 CPS	0.000	DEG F
11	OCT05.90	11:03:44	0	TEMP	0.000 CPS	0.000	DEG F
12	OCT05.90	11:03:44	0	RES	0.000 CPS	0.000	OHM
13	OCT05.90	11:03:44	0	RES	0.000 CPS	0.000	OHM
14			0		0.000 CPS	0.000	

STATE OF NORTH CAROLINA
DEPARTMENT OF ENVIRONMENT HEALTH
AND NATURAL RESOURCES
DIVISION OF ENVIRONMENTAL MGMT.
GROUNDWATER SECTION
512 NORTH SALISBURY STREET
ARCHADALE BLDG., ROOM 826
P.O. BOX 27687, RALEIGH NC 27611

RO- Test Well # 1

COMPANY : Cape Hatteras Water Associatio
WELL : RO- Test Well # 1
LOCATION/FIELD : North Frisco ocean side
COUNTY : DARE
STATE : NC
SECTION :

OTHER SERVICES:
-
-

TOWNSHIP :
RANGE :

DATE : 04/07/95
DEPTH DRILLER : 255
LOG BOTTOM : [illegible]
LOG TOP : 9.40

PERMANENT DATUM : msl
ELEV. PERM. DATUM: 0.00
LOG MEASURED FROM: [illegible]
DRL MEASURED FROM: -

ELEVATIONS
KB :
DF :
GL : 5

CASING DRILLER : 49
CASING TYPE : PVC
CASING THICKNESS: 40

LOGGING UNIT : 0111
FIELD OFFICE : WRO/CO
RECORDED BY : mike vaught

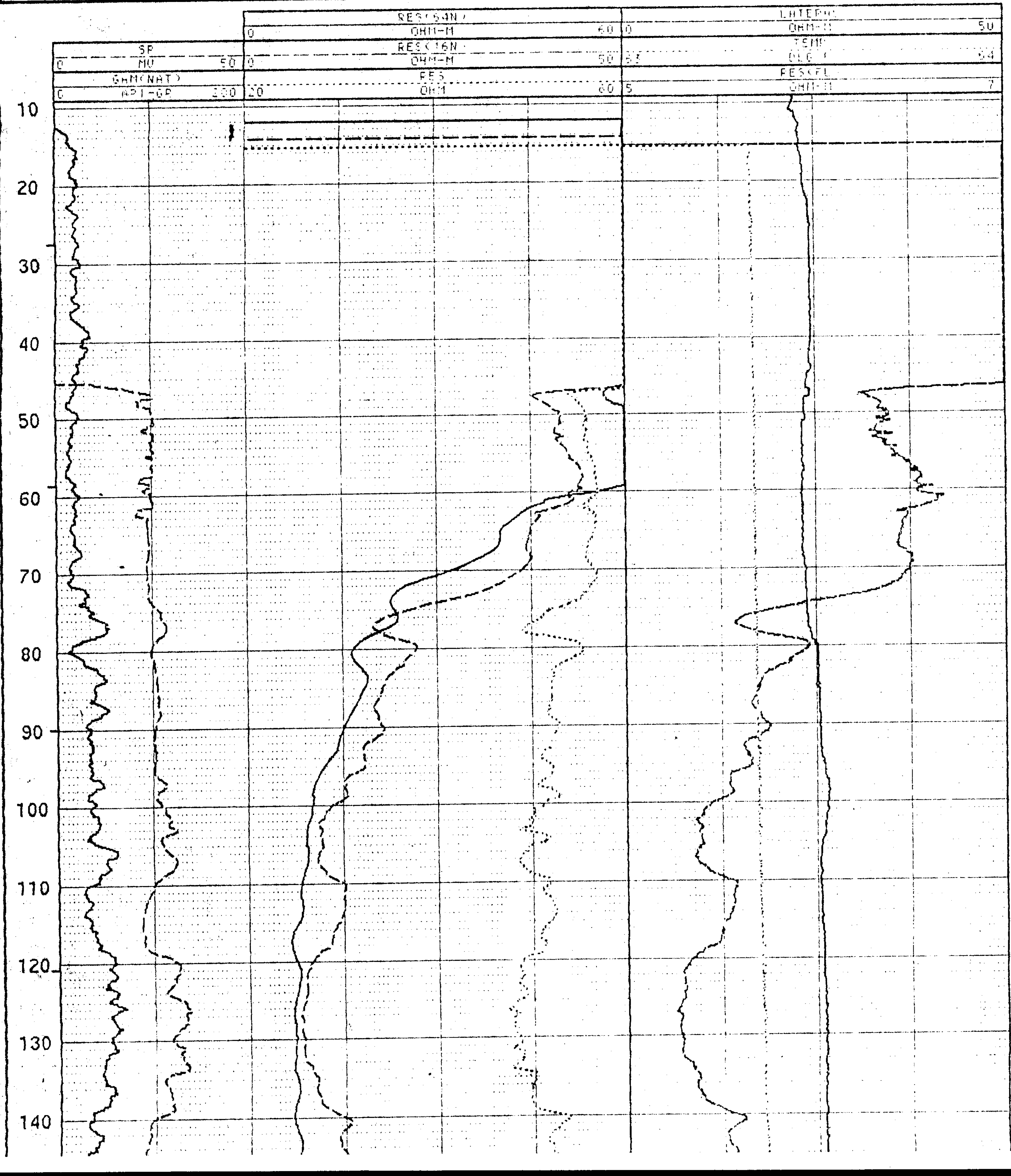
BIT SIZE : 9.5
MAGNETIC DECL. :
MATRIX DENSITY :
FLUID DENSITY : 9
NEUTRON MATRIX :

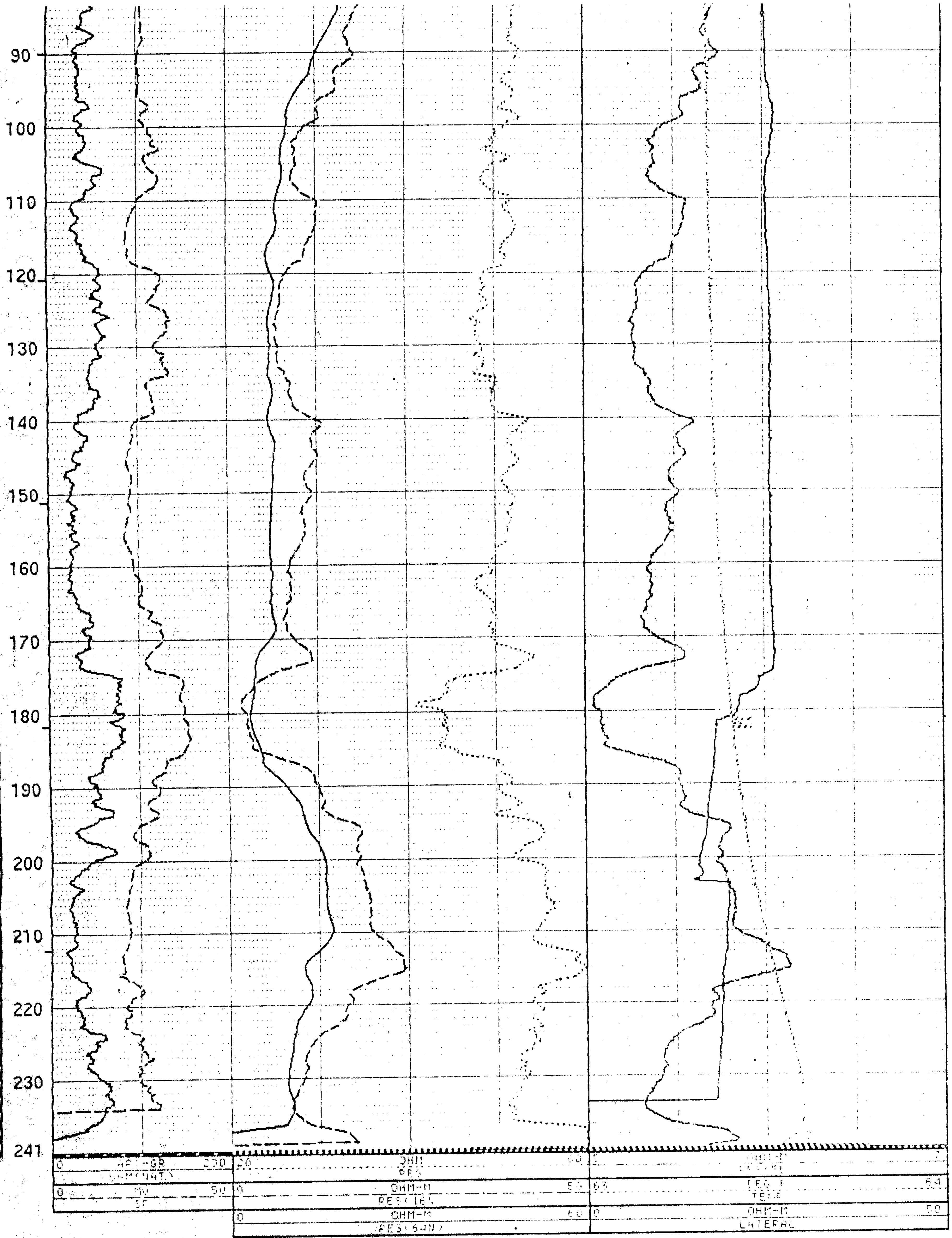
BOREHOLE FLUID : Ben
RM :
RM TEMPERATURE :
MATRIX DELTA T :
FLUID DELTA T :

FILE : ORIGINAL
TYPE : 9041A
LOG : 5
PLOT : 9041A 0
THRESH: 999999

REMARKS :
From Hwy 12 in north Frisco take Water Assoc Rd on the ocean side Approx 100yd
The hole caved in @ 250 lots of trouble drilling had to log top then case it

ALL SERVICES PROVIDED SUBJECT TO STANDARD TERMS AND CONDITIONS





TOOL CALIBRATION TOOL = 9041A SERIAL NUMBER = 273

	CAL-DATE	CAL-TIME	SRCE	SENSOR	RESPONSE	STANDARD	
0	OCT05.90	11:03:44	0	GAM(NAT)	0.000 CPS	0.000	API-GR
1	OCT05.90	11:03:44	0	GAM(NAT)	0.000 CPS	0.000	API-GR
2	OCT05.90	11:03:44	0	RES(FL)	0.000 CPS	0.000	OHM-M
3	OCT05.90	11:03:44	0	RES(FL)	0.000 CPS	0.000	OHM-M
4	OCT05.90	11:03:44	0	SP	0.000 CPS	0.000	MV
5	OCT05.90	11:03:44	0	SP	0.000 CPS	0.000	MV
6	OCT05.90	11:03:44	0	RES(16N)	0.000 CPS	0.000	OHM-M
7	OCT05.90	11:03:44	0	RES(16N)	0.000 CPS	0.000	OHM-M
8	OCT05.90	11:03:44	0	RES(64N)	0.000 CPS	0.000	OHM-M
9	OCT05.90	11:03:44	0	RES(64N)	0.000 CPS	0.000	OHM-M
10	OCT05.90	11:03:44	0	TEMP	0.000 CPS	0.000	DEG F
11	OCT05.90	11:03:44	0	TEMP	0.000 CPS	0.000	DEG F
12	OCT05.90	11:03:44	0	RES	0.000 CPS	0.000	OHM
13	OCT05.90	11:03:44	0	RES	0.000 CPS	0.000	OHM
14			0		0.000 CPS	0.000	