INVESTIGATION AND PREDICTIVE MODELING OF WATER QUALITY CHANGES WITHIN THE YORKTOWN AQUIFER, DARE COUNTY, NORTH CAROLINA

VOLUME I

PREPARED FOR:

COUNTY OF DARE
WATER PRODUCTION DEPARTMENT
600 MUSTIAN ST.
KILL DEVIL HILLS, NC 27948

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Project Number
CH0-401

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I. CONCLUSIONS AND RECOMMENDATIONS

The current annual average withdrawal rate from Baum Tract wellfield is 2.36 million gallons per day. Upward leakage of water of higher salinity from beneath the wellfield has increased total dissolved solids by approximately 1.4 milligrams per liter per day, or about 500 milligrams per liter per year, during the first two years of production from the wellfield. Solute transport modeling indicates that for this wellfield configuration, the total dissolved solids concentration increases will continue at rates depending on wellfield pumpage and the distribution of wellfield withdrawals. If potable demand and water quality changes continue at present rates, the Reverse Osmosis Water Treatment Plant will experience declines in production efficiency, accompanied by increasing operational costs, until feedwater quality changes (approximately 6000 milligram/liter total dissolved solids) necessitates substantial modification of the R.O. facility by late 1997. If demand for potable water increases, the rate of water quality change will also increase, and Treatment Plant operational costs will rise accordingly. It is imperative that mitigation of these effects by implemention of the outlined recommendations be undertaken as soon as possible in order to maintain treatment plant capacity, to minimize future capital costs, and to minimize on-going operational costs.

To minimize deterioration of feedwater quality, drawdown in the Baum Tract wellfield should be reduced. Limiting the annual average groundwater withdrawals to approximately 1.5 million gallons per day, and holding the peak demand pumpage to approximately 2.3 million gallons per day, will allow efficient treatment of Baum Tract water at the present R.O. facility until around the turn of the century. R.O. supply wells 4, 5, and 6 have the highest total dissolved solids concentrations. These wells should be removed from primary use status in order to reduce the overall wellfield pumpage to the recommended 1.5 million gallons per day annual average. Primary withdrawals should be transferred to wells with the greatest well spacings and lowest total dissolved solids concentrations. Supply wells 4, 5, and

6 should be maintained in ready status for emergency stand-by or back-up production capacity. Water quality sampling should continue in these wells. If the total dissolved solids concentration in any of the five supply wells changes in time and significantly exceeds the concentration monitored in wells 4, 5, or 6, the standby status should be rotated to the well with the highest concentration, and pumpage should continue from the wells with the lowest total dissolved solids concentrations. An alternative pumping scheme would be to reduce the maximum pumping rates from each well and operate more wells concurrently to meet a given feedwater requirement. This would distribute the pressure reduction over a larger area, reducing the pressure gradients under individual wells, and minimizing the rate of water quality decline. This may require using three wells to supply each R.O. train instead of the existing configuration of two wells per train.

The 1.2 million gallons per day feedwater requirement created by this withdrawal limitation on the existing wellfield should be made up using two new well sites located approximately one to two miles south of the R.O. plant. The new wells should be placed in a linear configuration parallel to the coast with a well spacing of at least 1500 feet. Kill Devil Hills and Nags Head municipal property adjacent to Fresh Pond are recommended for the new well sites.

Prior to installation of the new supply wells, two four-inch diameter test wells should be installed at the new wellfield site. Data collected during the installation of these wells be used to determine any lateral changes in the lithology or water quality within the Yorktown Aquifer, determine the total dissolved solids profile at the site, and help determine the optimal production zone interval. These wells will serve as monitor wells after installation of the new supply wells, and serve as observation wells during aquifer testing of the new wells, allowing for determination of aquifer parameters at the new site.

When expansion of raw water facilities is required to meet increasing demand, then additional wells should be installed along this alignment to the southeast, using a well spacing of approximately 1500 foot spacing as site availability dictates. Assuming that the water quality at the new sites is similar to that at the Baum Tract, installation of the new wells should significantly extend the Baum Tract wellfield life by providing the R.O. plant with an improved quality feedwater blend after mixing with the relatively fresh water from the new wellfield. Using the combination of wellfields, the feedwater mix should remain within R.O. plant operational criteria (6000 milligrams per liter total dissolved solids) until approximately 2005. Before the 6000 milligram per liter feedwater total dissolved solids concentration occurs, the wellfield should be expanded, R.O. plant modifications should be made, or technology improvements should be implemented to assure an uninterrupted supply of treated water.

Depending on the site-specific geology and the total dissolved solids profile at the new well sites, new well screens may be limited to lengths of under 100 feet, and the screens should be accurately positioned at the top of the mid-Yorktown aquifer. Any reductions in screen lengths may require slight downsizing of the individual pump capacities. A shallower setting for the base of the screened interval will put a greater thickness of sediment between the production zone and the higher salinity water occurring deeper in the aquifer system. It may also tap a fresher interval, initially resulting in production of water with a total dissolved solids concentration of less than 2000 milligrams per liter. Together with the increased well spacing, these changes will significantly decrease the rate at which total dissolved solids concentrations change.

Water quality data should be collected in monitor wells OBS-300 AND OBS-600 to provide background data on the quality of the Yorktown Aquifer in the area between supply wells. These data will be useful for determining the site specific nature of the saline water upconing by revealing the extent to which upconing is occurring immediately beneath the supply wells, as opposed to upward leakage of saline water into the production interval over the entire wellfield zone of influence.

Production well pumping status (on/off and rate) at the time water level measurements are made and should continue to be recorded. Water level measurements in all supply and monitor wells in the wellfield should be sampled on the same day if possible. A minimum of three well volumes of water should be purged from the monitor wells prior to sampling. This is particularly important for OBS-300, OBS-600, and the Ocean Monitor Well, because these wells have screens which fully penetrate the Yorktown Aquifer production zone, and density stratification within the well casings can cause falsely low total dissolved solids measurements to be made if they are not sufficiently purged.

To improve the water level data set, a land survey of all supply well and monitor well measuring points to National Geodetic Vertical Datum (N.G.V.D) should be performed. This will permit depth to water measurements to be converted to absolute water levels. Water level measurements after periods of wellfield shutdown will allow determination of the recovery of aquifer pressure. Differences between these water levels and the pre-development water levels will improve understanding of the true hydraulic boundary conditions.

II. INTRODUCTION

Project History

In 1987, as part of a continuing hydrogeologic investigation of the Yorktown Aquifer for reverse osmosis water supply development, Missimer & Associates, Inc. performed an evaluation of the long term changes in water quality which might result from pumping the Yorktown Aquifer system beneath the Outer Banks at Kill Devil Hills. That evaluation was based on very limited data available from government sources, and site-specific hydrologic testing performed by Missimer & Associates, Inc. staff and others.

Since 1987 the Dare County Water Production Department has developed a strong data base resulting from a comprehensive program of monitoring water levels and water quality within the wellfield area. A preliminary evaluation suggests that the upward component of leakage beneath the wellfield production zone may be contributing to this decline in water quality. This change in water quality occurs because the Yorktown Formation is stratified with respect to total dissolved solids, with relatively fresh water occurring in its upper reaches, and with higher salinity water occurring deeper in the formation.

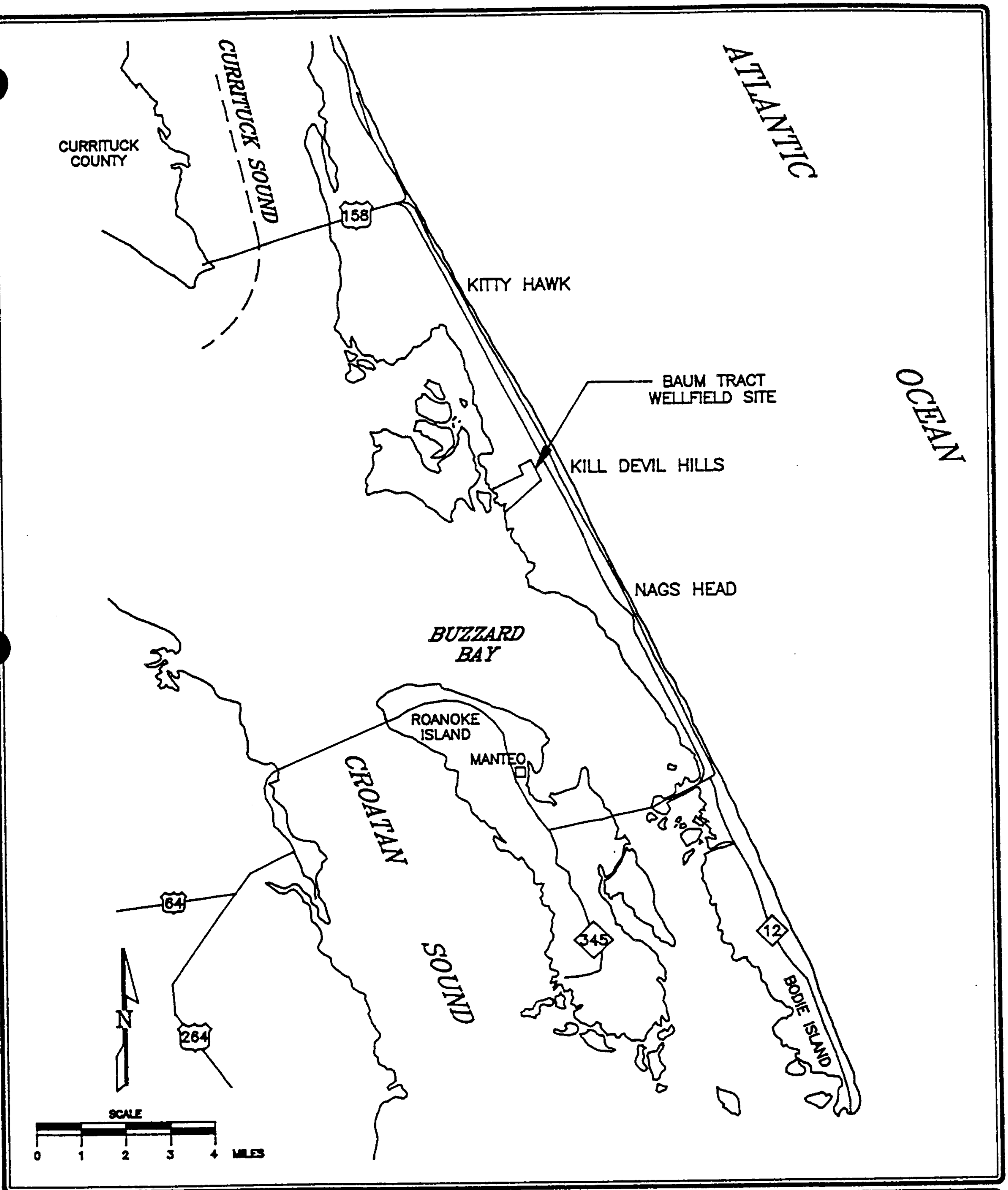
Project Scope

The purpose of this report is to present our analysis of the hydrogeology of the Yorktown Aquifer in the vicinity of the Dare County Reverse Osmosis Water Treatment Plant wellfield. It includes a discussion of the evolving quality of the feedwater stream and the hydrogeologic components which influence this water quality. A three-dimensional flow and transport model is used to simulate the hydraulic flow field and the changing water quality in the existing wellfield. The model was calibrated with respect to flow and transport, is then used in a predictive mode to test alternative wellfield configurations in order to determine an optimal wellfield development program and aquifer management policy which will keep further changes in feedwater quality to a minimum.

The model area includes northeastern Dare County and southern Currituck County, and is centered on the Reverse Osmosis Plant feedwater supply wellfield, extending up to seven miles beyond the wellfield in all directions (Figures 2-1 and 2-2). Model simulations for calibration purposes were made of the pumpage period between wellfield start-up in August, 1989, and the end of September, 1991. Predictive simulations were then run for the period from October, 1991, through October, 2003.

Acknowledgements

The present study was conducted using information from a variety of sources. Bob Oreskovich, Superintendent of the Dare County Water Production Department, was extremely helpful in providing wellfield records and operations information. Additional information was provided by Pat Erwin and Nancy Loomis, also of the Water Production Department. Matt Wilson of the North Carolina Department of Environmental Health and Natural Resources, Division of Water Resources, provided information concerning recent publications relating to North Carolina coastal plain hydrogeology in general, and Currituck County/Outer Banks water supply studies in particular.



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ENVIRONMENTAL AND GROUNDWATER SERVICES

DRN. BY: JCS DWG NO. A-C0401DXF-2 DATE: 3/3/92

PROJECT NAME: DARE COUNTY R.O. WELLFIELD NUMBER: CH0-401

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FIGURE 2-1. GENERAL LOCATION MAP OF NORTHERN DARE COUNTY OUTER BANKS.

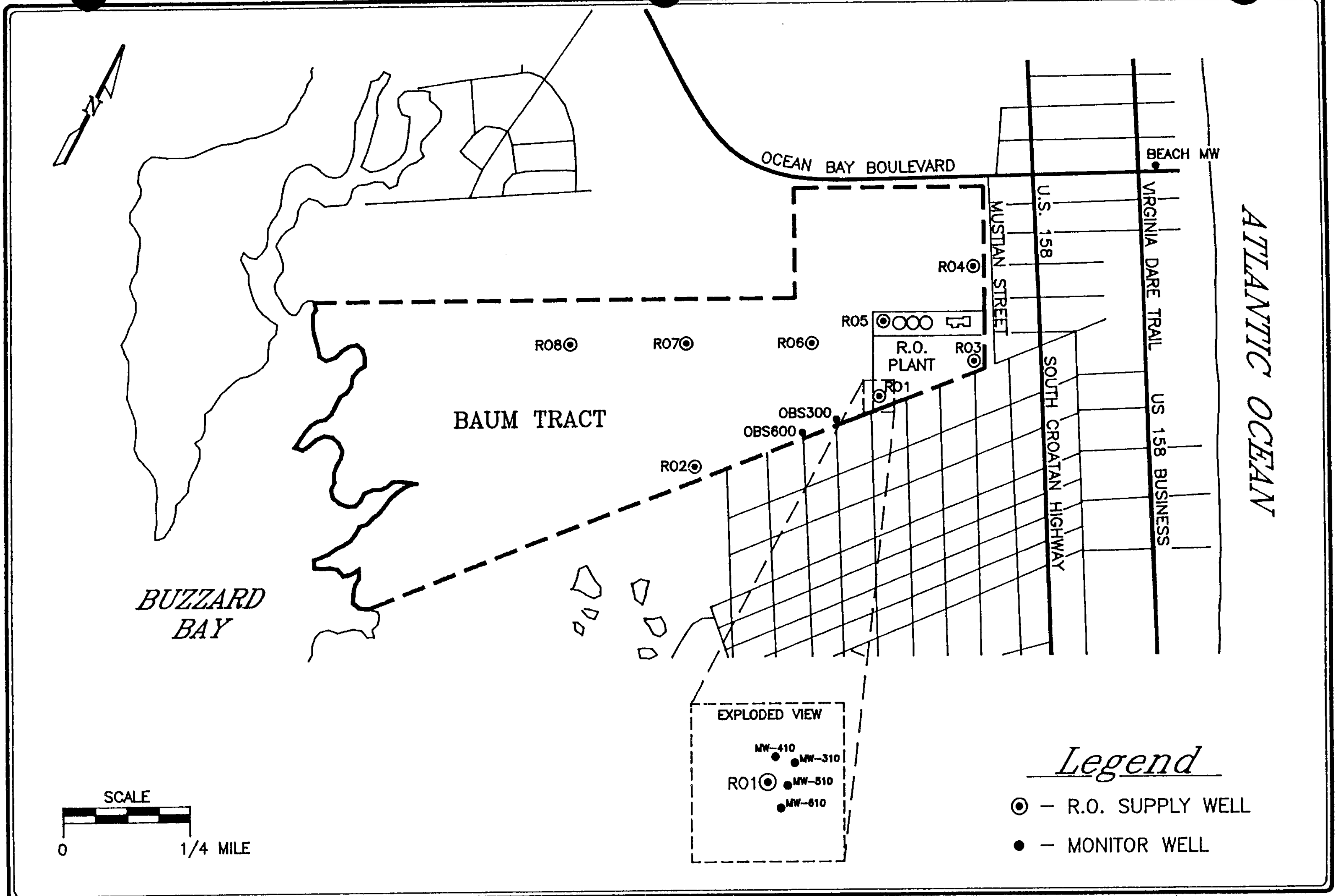

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FIGURE 2-2. WELLFIELD LOCATION MAP.

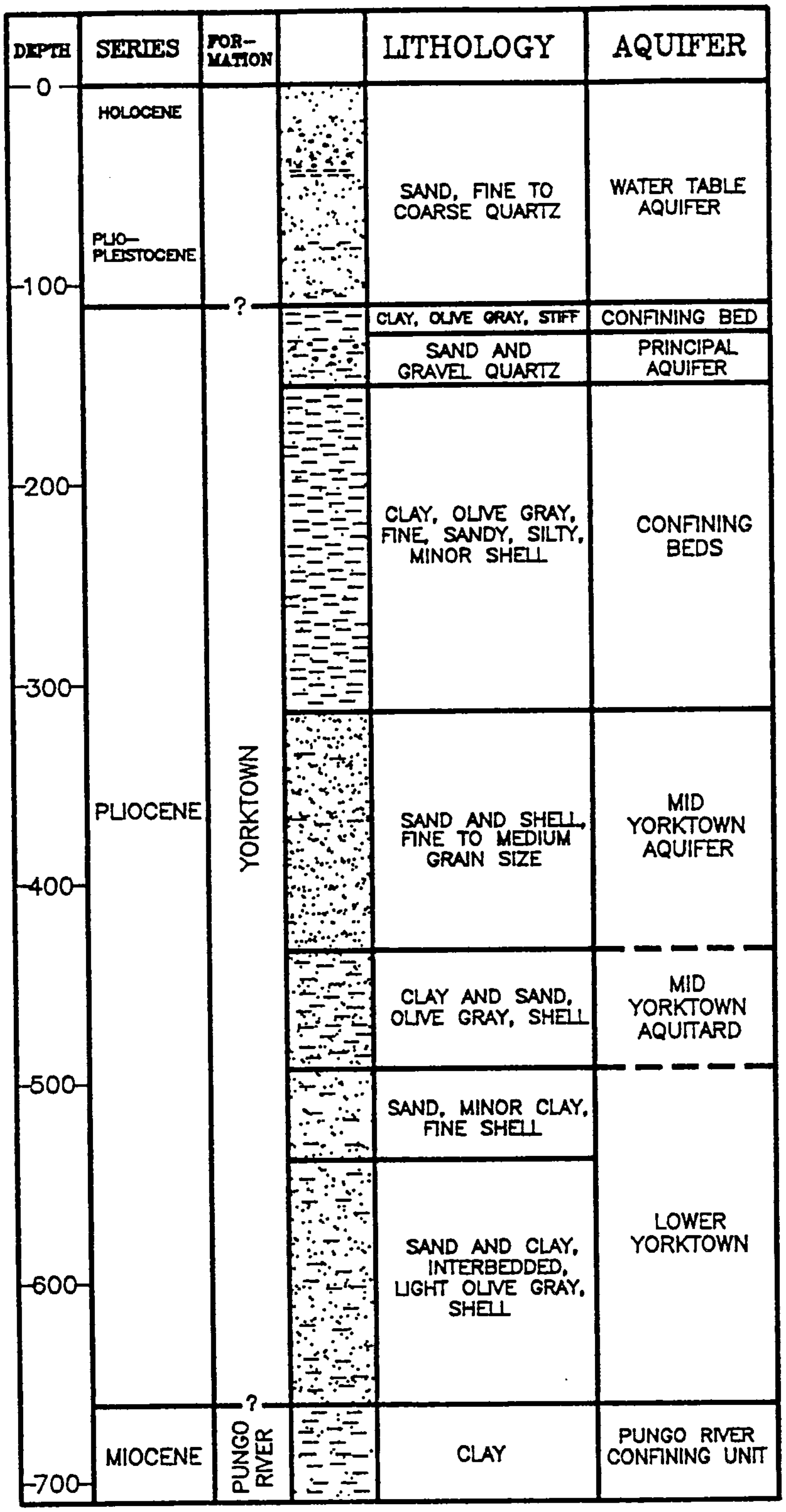
III. HYDROGEOLOGY AT KILL DEVIL HILLS

Introduction

Hydrogeologic investigations at Kill Devil Hills have been conducted by the North Carolina Department of Environment, Health, and Natural Resources, Division of Water Resources, the U.S. Geological Survey, and various consultants including Missimer & Associates, Inc. The object of some of the most recent investigations was to determine the suitability of the Yorktown Aquifer for use as a resource for reverse osmosis water treatment. Important issues were the nature and distribution of water quality laterally and with depth, the degree of confinement above the Yorktown Aquifer, the degree of confinement between the mid-Yorktown Formation and the lower-Yorktown Formation, and the confinement between the Yorktown Aquifer and the underlying Pungo River Formation.

The Yorktown Formation of Pliocene age underlies the more recent surficial deposits. It ranges in thickness from about 150 feet thick in Beaufort County, to over 500 feet thick in eastern Dare County. The Yorktown Formation consists of beds of fine to coarse-grained sand and sandy limestone interbedded with clay, with widely distributed mollusk shells. Sand and limestone layers in the Yorktown are the principal source of water supply in Hyde and Tyrell Counties, and to a lesser extent in Washington County. Dare County is the only user of this aquifer in the Outer Banks area. The distances separating inland users of the Yorktown Aquifer from the Dare County wellfield at Kill Devil Hills are sufficiently great that there are no direct interactions between them. For a more detailed description please see Winner & Coble, 1989.

The most reliable and site specific source of geologic information about the Yorktown Formation at Kill Devil Hills comes from the lithologic log acquired by Missimer & Associates during the construction of R.O. well 1. A geologic column based on this log is shown in Figure 3-1. Geophysical logging in R.O. Well 1 is



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ENVIRONMENTAL AND GROUNDWATER SERVICES

DRN. BY: CAM DWG NO. C-C0401GE2-3 DATE: 3/24/92

PROJECT NAME: DARE COUNTY, NORTH CAROLINA NUMBER: CH0-401

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FIGURE 3-1. HYDROGEOLOGIC SECTION OF DARE COUNTY BAUM TRACT WELLFIELD.

used together with a suite of geophysical logs performed in the 1610 foot Deep Test well (KDH-DTH) and the U.S.Geological Survey site 11 well to provide additional lithologic information, particularly about the strata underlying the Yorktown Aquifer production zone.

The Yorktown Formation confining beds consist of thick olive-gray marine clays with fine sand and silt interbeds beginning at a depth of 150 feet, and continuing to a depth of approximately 320 feet. These beds have a very low vertical hydraulic conductivity, and effectively isolate the underlying Yorktown Aquifer from saline water in the near surface sediments. The mid-Yorktown Aquifer (formerly called the Lower Aquifer) begins at the top of the transmissive sand unit at a depth of approximately 320 feet, and continues to about 440 feet. A clay and sand bed occurring between 440 and 500 feet below land surface (BLS) impedes the vertical movement of water, and acts as an aquitard. Below this aquitard a transmissive, thirty foot thick sand and shell bed occurs, between 500 and 530 feet BLS. Finally, near the base of the Yorktown Formation, an interbedded sand and clay unit occurs having moderate transmissivity. The Pungo River confining beds mark the lowermost limit of the Yorktown Formation. These beds begin at a depth of 660 feet BLS, based on the natural gamma-ray log from the deep test well (KDH-DT). For a more detailed description of the Yorktown Formation at Kill Devil Hills see Peek, Register, and Nelson (1972), and Missimer & Associates, Inc. (1987).

In this report the terms "mid-Yorktown" and "mid-Yorktown Aquifer" are used to refer to the sand and shell bed between 320 and 440 feet BLS; the clay and sand unit between 440 and 500 feet BLS is referred to as the "mid-Yorktown aquitard"; and the term "lower-Yorktown Aquifer" is used to refer to the clayey sand beds and the transmissive sand and shell sequence between 500 and 660 feet BLS.

Relatively little is known about regional hydraulic gradient of the Yorktown Aquifer, but in the Outer Banks area it is subdued, probably less than one foot per mile.

Water levels in the wells which penetrate the Yorktown Aquifer at Kill Devil Hills cannot be readily converted to hydraulic gradients because many of these wells are not surveyed relative to National Geodetic Vertical Datum. However, because of the very low gradient this does not present a problem to the groundwater model; the model assumes a horizontal initial potentiometric surface.

Recharge to the Yorktown Aquifer occurs on the mainland west of Dare County, primarily from direct rainfall infiltration where the Yorktown Formation outcrops at land surface, but also from brackish to saline water from Albemarle Sound and leakage from stratigraphically adjacent aquifers. As noted, however, groundwater gradients are very low in the Outer Banks, and the rate of freshwater recharge to the brackish mid-Yorktown Aquifer at Kill Devil Hills is minimal.

Aquifer Hydraulic Parameters

Two aquifer performance tests have been performed using wells screened in the mid-Yorktown interval, from 320 to 420 feet below land surface in the Kill Devil Hills area. These tests produced a range of aquifer coefficients, varying from 99,000 to 160,000 gpd/ft for transmissivity, 3.4×10^{-4} to 4.5×10^{-4} for storativity, and 4.3×10^{-3} to 5.0×10^{-4} gpd/ft^3 for leakance. An additional test in Rodanthe determined a transmissivity value of between 70,000 and 89,000 gpd/ft, a storativity of 1.4×10^{-4}, and a leakance value of 2.1×10^{-3} gpd/ft^3. Based on lithologic data it is expected that values for leakance represent the degree of hydraulic connection between the production interval and the underlying sediments in the lower-Yorktown Formation, and not the degree of connection between the production interval and overlying Principal Aquifer or Quaternary units, or with the deeper underlying Pungo River Formation.

These measured hydrogeologic data, along with detailed analysis of lithologies and geophysical signature, were used to construct a calibrated numerical model with a hydraulic response which is virtually identical to the actual aquifer. The hydrogeologic data base is relatively strong in the mid-Yorktown Aquifer production zone, but the hydraulic character within the lower-Yorktown Aquifer, which exerts a significant influence on the production zone above, is largely unknown. The system modeled in this report is bounded by the thick Yorktown confining beds above the production interval (above 320 ft. BLS), and the Pungo River confining beds (below 660 ft. BLS).

IV. WELL DATA ANALYSIS

Introduction

Information collected weekly from fifteen wells (Figure 2-2) by the Dare County Water Department is critical to analysis of Yorktown Aquifer behavior. Water levels are measured in all eight supply wells, and the well pumping rate is recorded. Water levels are also measured in the seven monitor wells. Water samples are collected in the supply wells if they are pumping at the time of measurement. Water samples are collected from five of the seven monitor wells. These weekly water samples are analyzed for chloride concentration, total dissolved solids (TDS) and iron. A silt-density index determination is made once per month. The most important information for this study is the water level and water quality data collected from the seven observation wells, and the water quality data obtained from the eight production wells.

Three of the monitor wells (OBS-300, OBS-600, and OCEAN-MW) are fully screened across the production zone. Two monitor wells (MW-310 and MW-410) have short, ten foot long screens which tap the top and bottom of the production zone. Two additional clustered monitor wells (MW-510 and MW-610) have ten foot long screens at depths of 100 and 200 feet below the production zone. The screened intervals of these 15 wells are shown on Table 4-1.

Supply Well Pumping Rates

Data from the totalizing meters on the R.O. supply wells were used to establish the monthly pumpage from each well. Meter readings are made on pumping wells according to a weekly schedule. However, the schedule does not coincide with the last day of any month, and slight variations in the meter reading schedule and the omission of readings from non-pumping wells complicates the data set. Therefore, to standardize the data for each well on a monthly basis, linear interpolations of the meter readings were made to determine the gallons pumped from each well at the

TABLE 4-1. Well construction details and monitoring schedule

WELL	SCREENED INTERVAL (FEET BLS)	AQUIFER TAPPED	WEEKLY WATER LEVELS	WEEKLY WATER QUALITY
RO1	322-422	mid-Yorktown	X	X
RO2	326-427	mid-Yorktown	X	X
RO3	322-422	mid-Yorktown	X	X
RO4	318-419	mid-Yorktown	X	X
RO5	322-422	mid-Yorktown	X	X
RO6	318-419	mid-Yorktown	X	X
RO7	323-424	mid-Yorktown	X	X
RO8	320-421	mid-Yorktown	X	X
OBS300	320-420	mid-Yorktown	X	
OBS600	320-420	mid-Yorktown	X	
MW-310	310-320	top of mid-Yorktown	X	X
MW-410	400-410	base of mid-Yorktown	X	X
MW-510	495-505	top of lower-Yorktown	X	X
MW-610	610-620	base of lower-Yorktown	X	X
OCEAN	310-410	mid-Yorktown	X	X

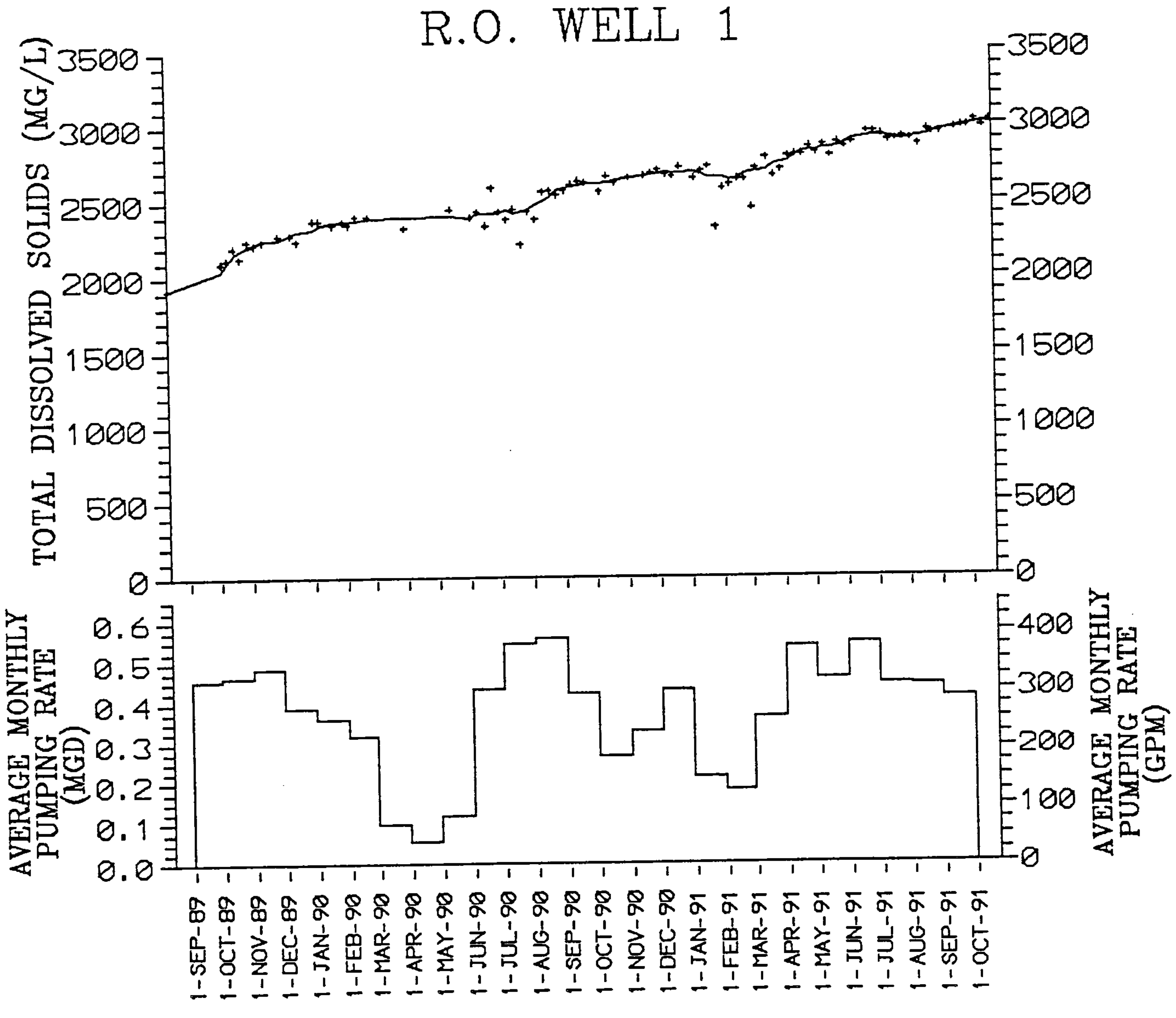
end of each month. These data are plotted as histograms of pumping rate versus time. The plots are shown together with the total dissolved solids water quality data for each well in Figures 4-1 through 4-8. Discussion of the TDS variations as related to pumping rate is given later in this section of the report.

Supply Well Pumping Levels

Measurements are made of the depth to water in the R.O supply wells on a weekly schedule. Plots of reported water level drawdowns versus time in relation to wellfield average pumping rates are shown in Figures 4-9 through 4-16. The solid line through these data is based on a five-point moving average after filtering to remove anomalous outlier points. These data are useful for showing the differences in water levels between the maximum and minimum pumpage rates, but they cannot be directly used for model calibration purposes due to the added variable of well efficiency. In addition, the lack of a common datum (NGVD) for the measuring points at each well, and the lack of a reproducible and uniformly determined static water level, makes analysis of the water level data problematic. Graphs of the production well water level data show characteristically strong correlation with the pumpage data.

Supply Well Specific Capacities

The specific capacity of a well is calculated by dividing well pumping rate by drawdown from static water level, and it is a useful measure of well performance. Specific capacity determinations for the R.O. supply wells have been made by the Water Production Department. The specific capacity calculations are based on well drawdown, which is the pumping level (depth to water) minus the static water level. Static water levels are determined on different dates by shutting down the entire wellfield for a few hours, allowing the Yorktown Aquifer to recover some of its potentiometric head, then measuring depth to water in all the wells. Average pumping level for all wells, after adjustment of the average value in each well to a common average for all eight wells, is shown in Figure 4-17.



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PROJECT NAME: DARE COUNTY WELLFIELD NUMBER: CH0-401

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FIGURE 4-1. R.O. WELL 1 TOTAL DISSOLVED SOLIDS CONCENTRATION AND MONTHLY AVERAGE PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

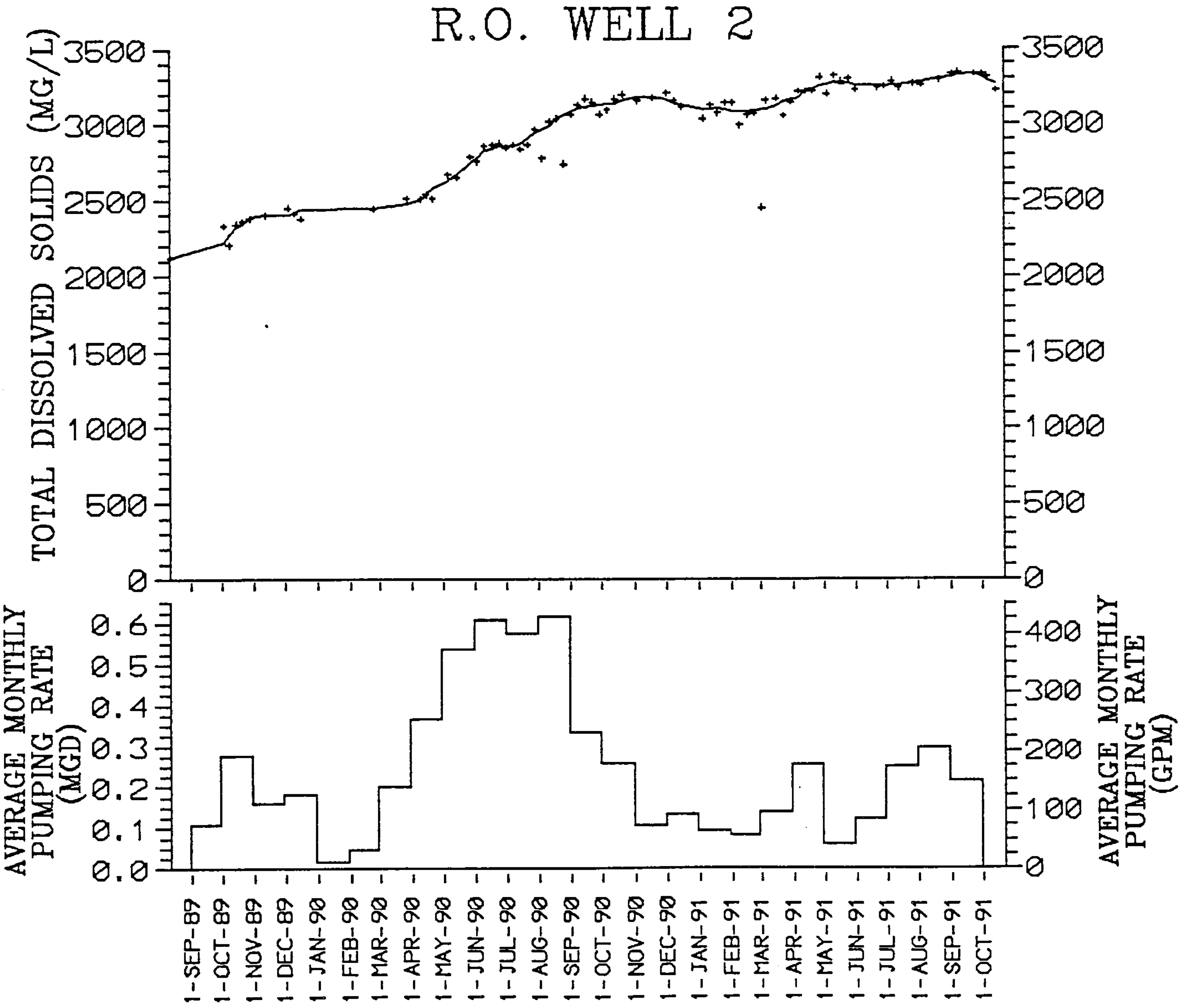

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FIGURE 4-2. R.O. WELL 2 TOTAL DISSOLVED SOLIDS CONCENTRATION AND MONTHLY AVERAGE PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

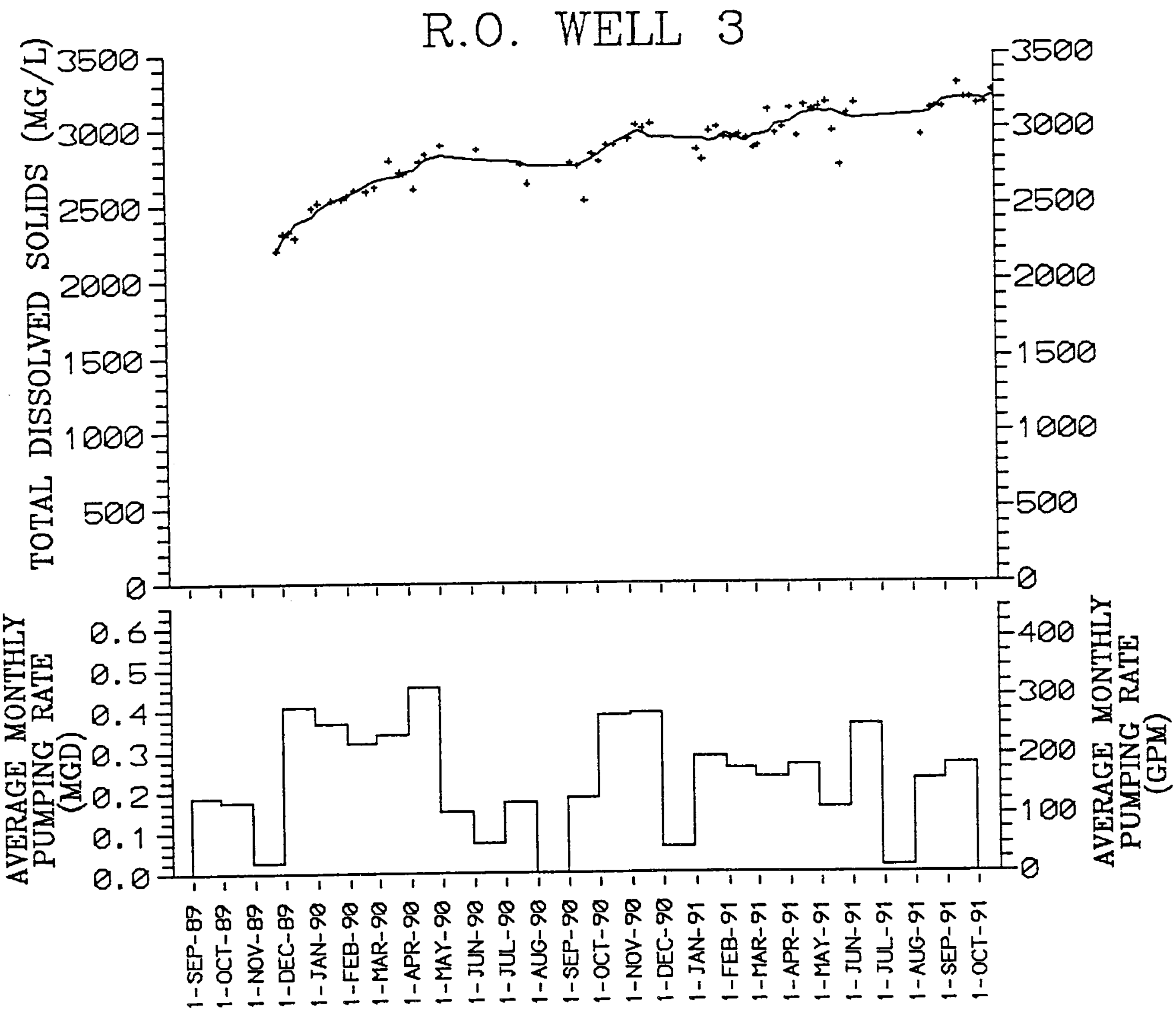

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FIGURE 4-3. R.O. WELL 3 TOTAL DISSOLVED SOLIDS CONCENTRATION AND MONTHLY AVERAGE PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

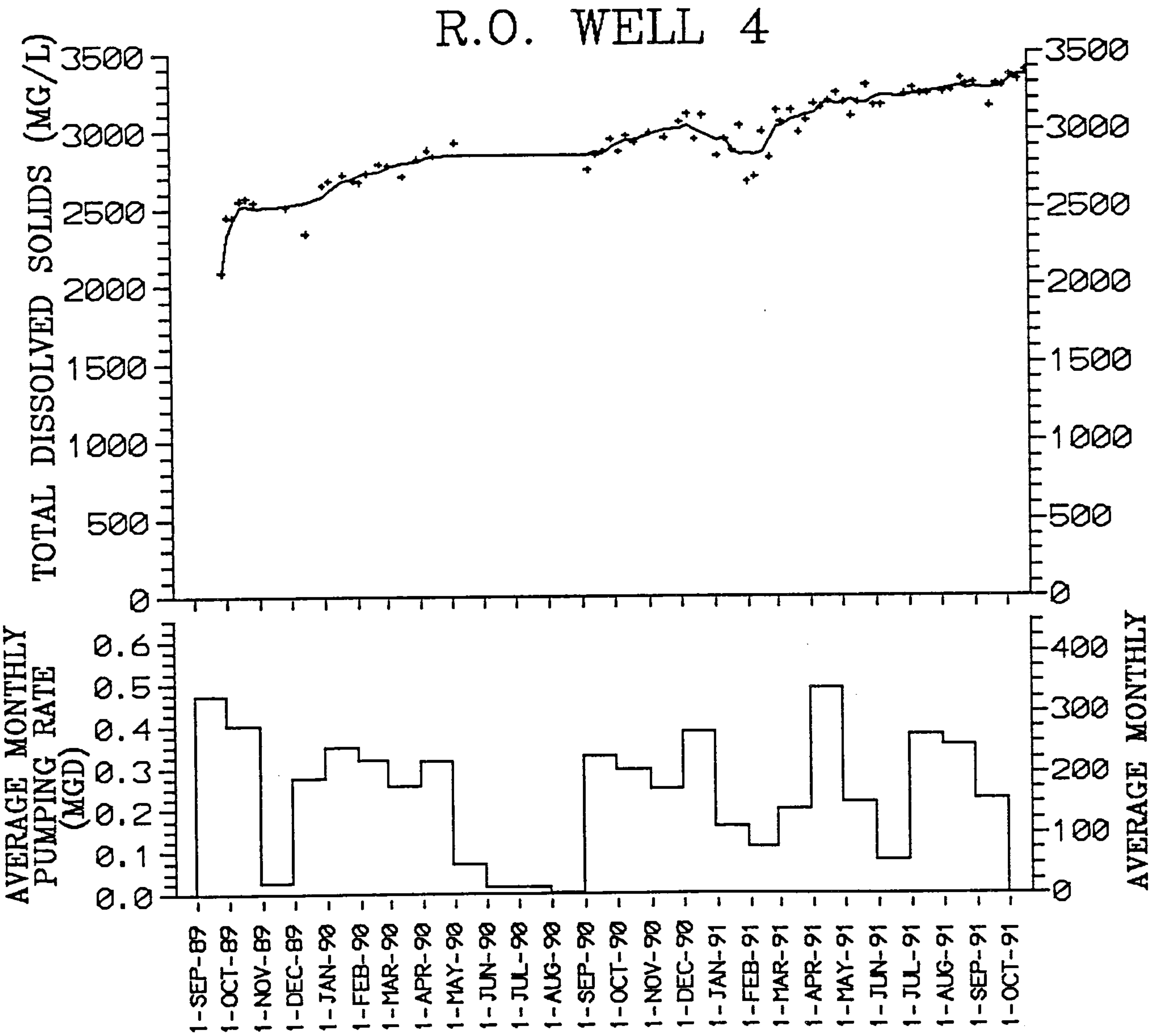

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FIGURE 4-4. R.O. WELL 4 TOTAL DISSOLVED SOLIDS CONCENTRATION AND MONTHLY AVERAGE PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

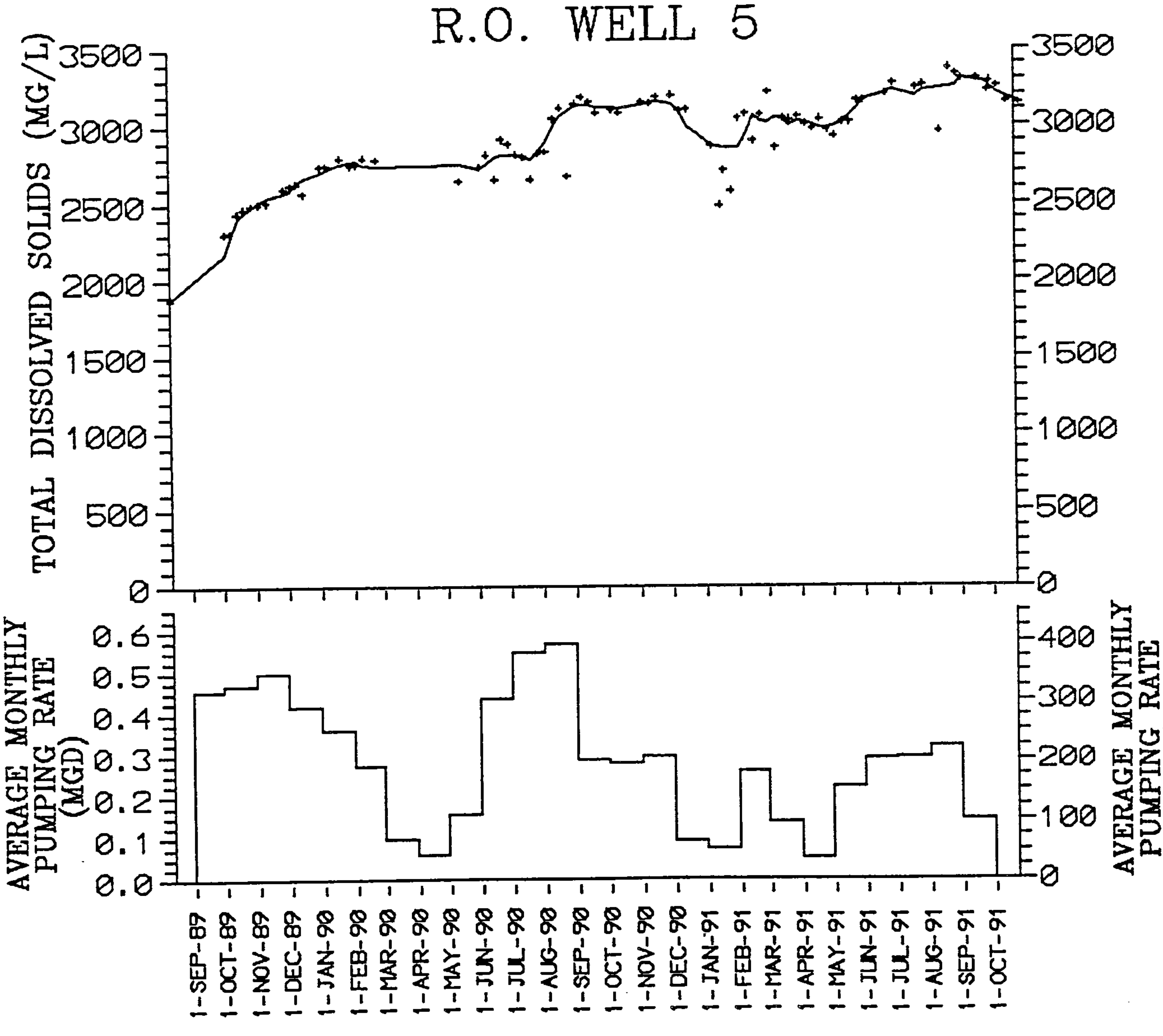

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FIGURE 4-5. R.O. WELL 5 TOTAL DISSOLVED SOLIDS CONCENTRATION AND MONTHLY AVERAGE PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

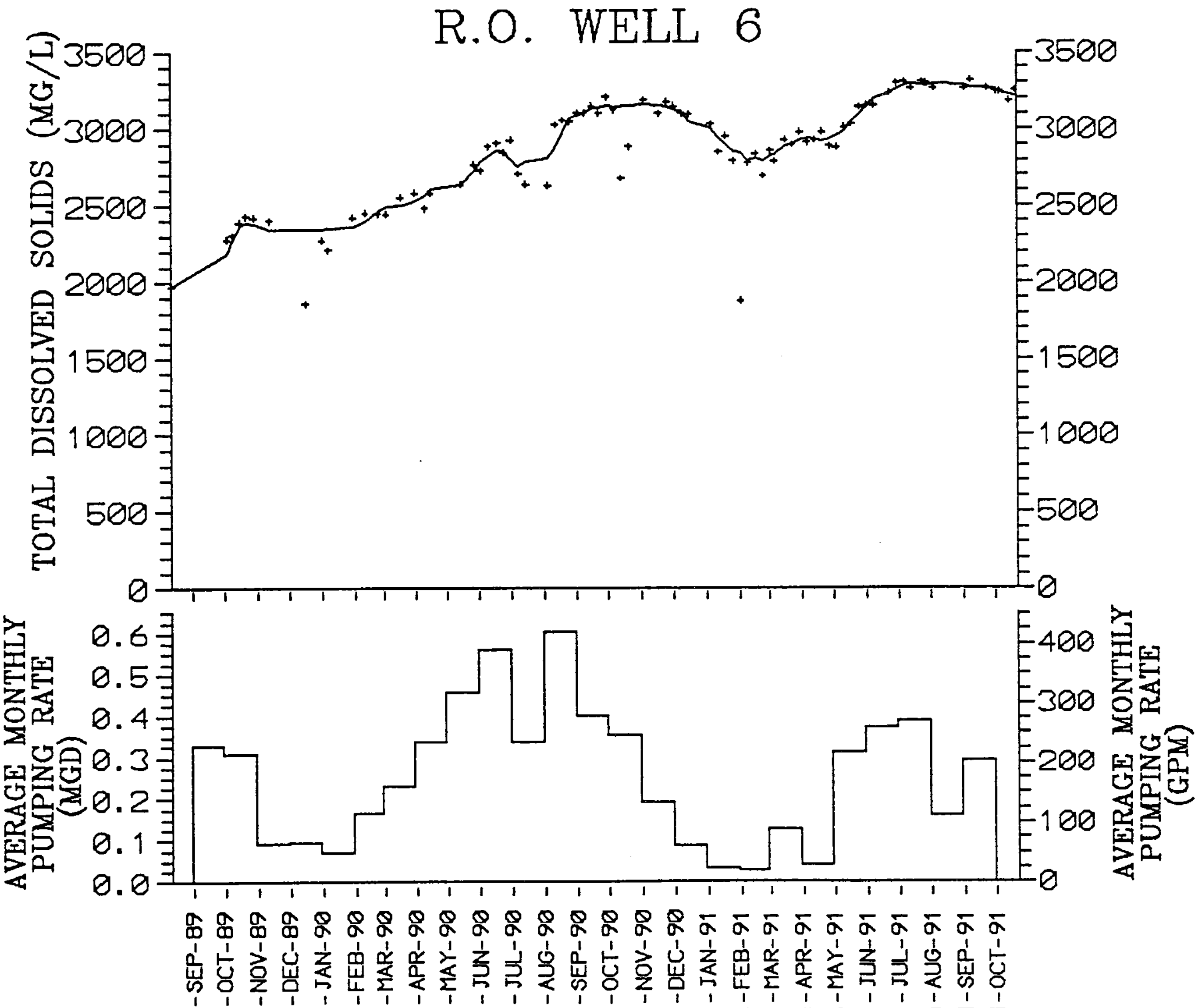

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FIGURE 4-6. R.O. WELL 6 TOTAL DISSOLVED SOLIDS CONCENTRATION AND MONTHLY AVERAGE PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

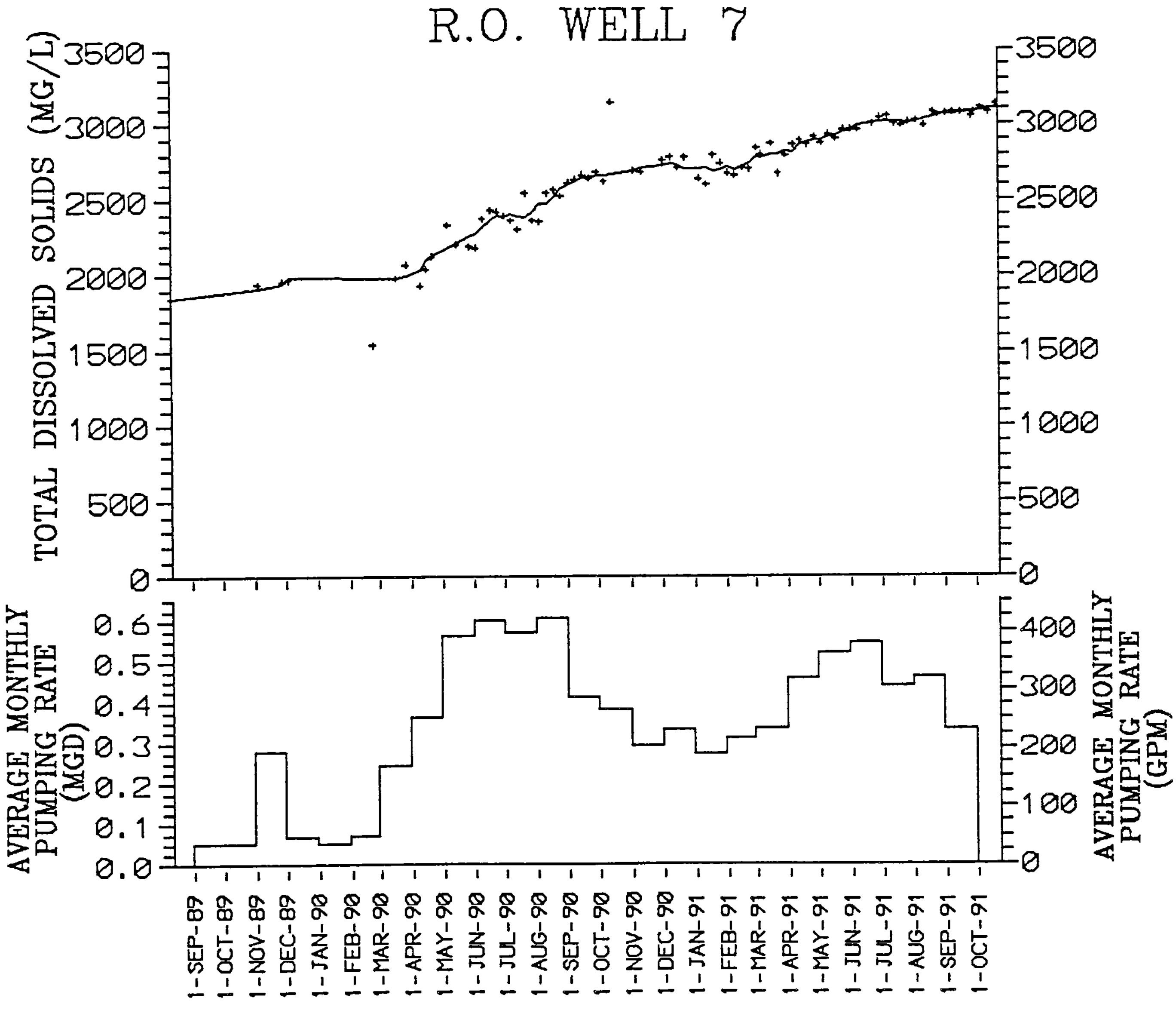

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FIGURE 4-7. R.O. WELL 7 TOTAL DISSOLVED SOLIDS CONCENTRATION AND MONTHLY AVERAGE PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

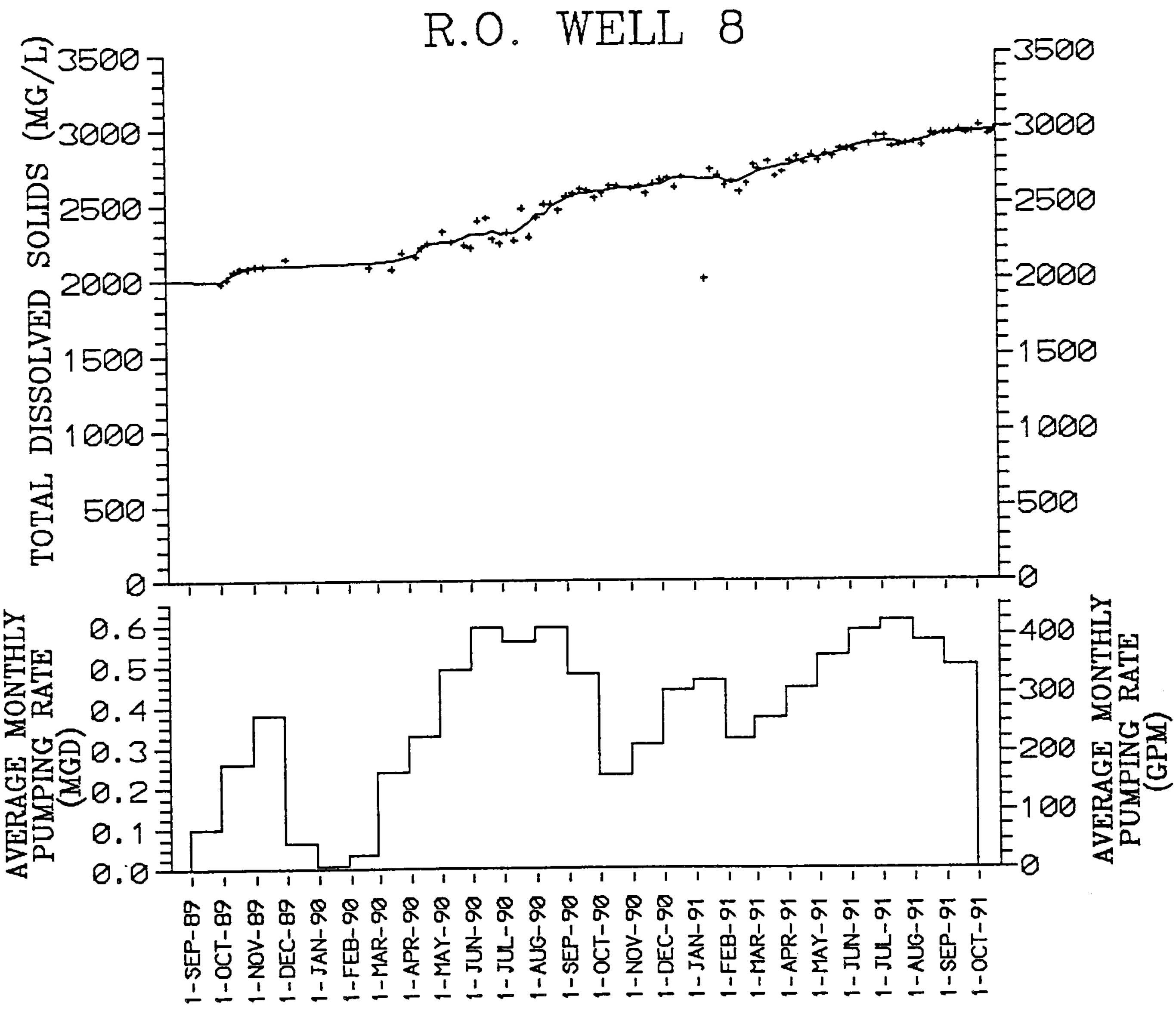

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FIGURE 4-8. R.O. WELL 8 TOTAL DISSOLVED SOLIDS CONCENTRATION AND MONTHLY AVERAGE PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

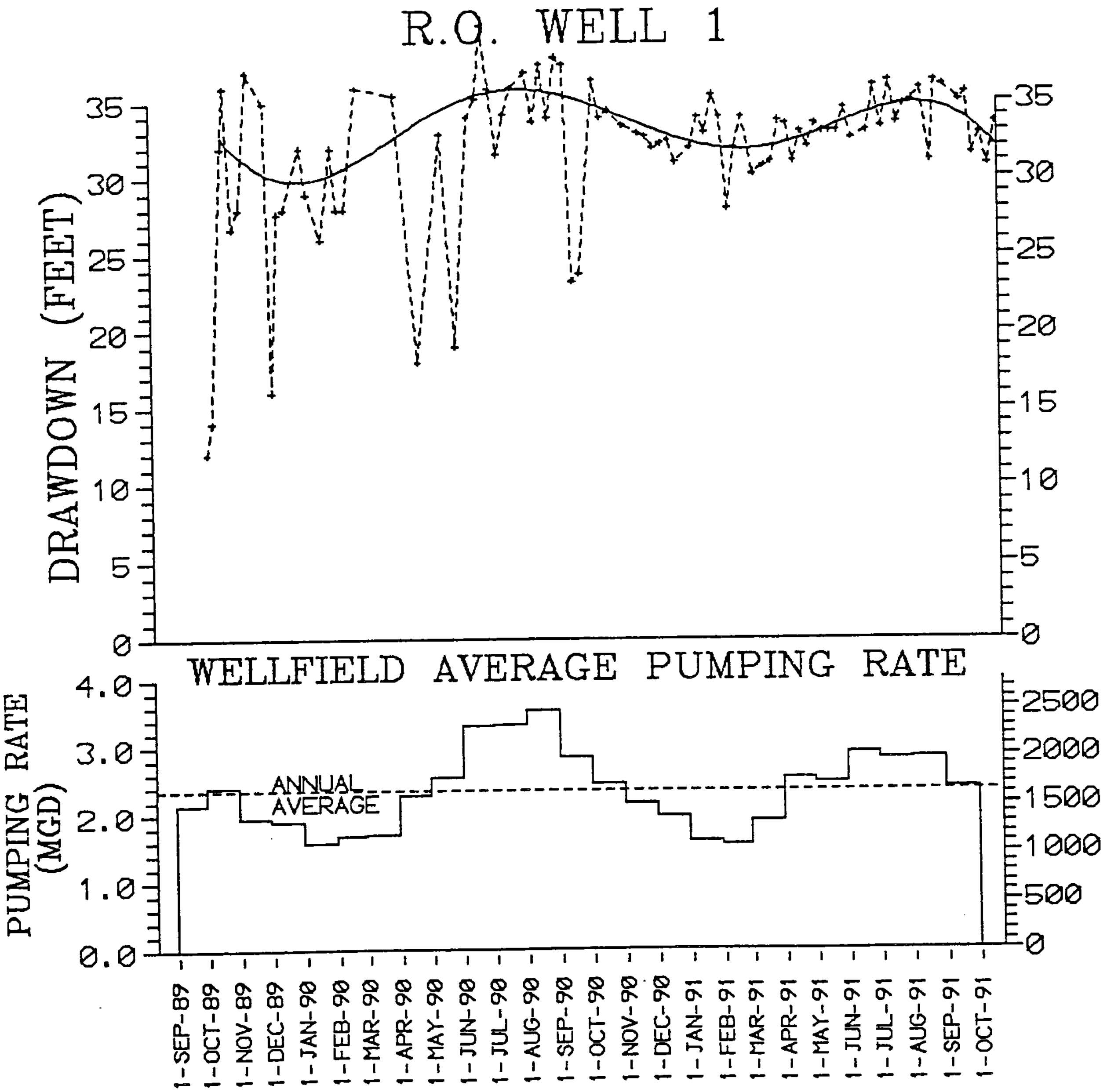

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FIGURE 4-9. REPORTED R.O. WELL 1 DRAWDOWN AND MONTHLY AVERAGE WELLFIELD PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

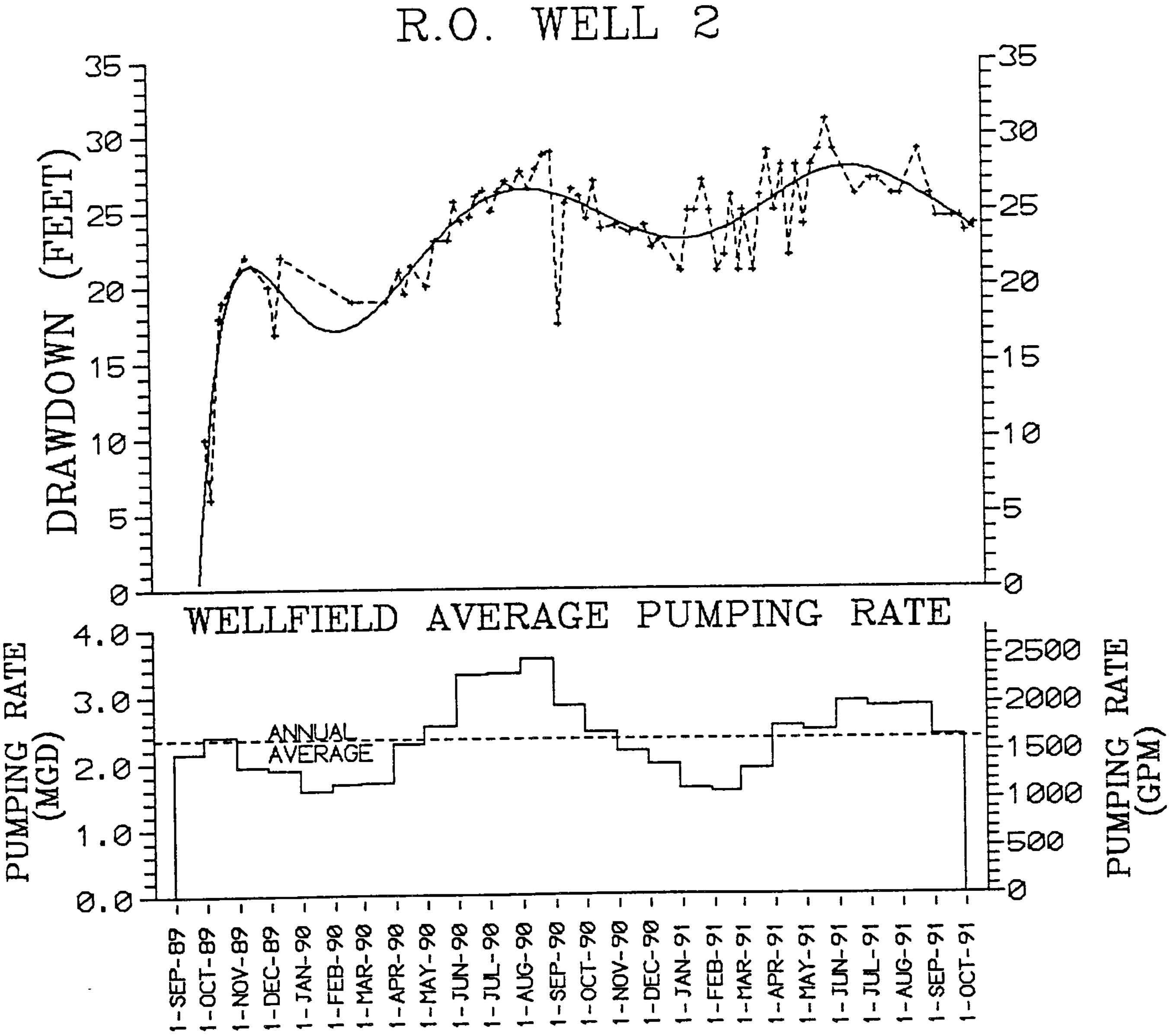

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FIGURE 4-10. REPORTED R.O. WELL 2 DRAWDOWN AND MONTHLY AVERAGE WELLFIELD PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

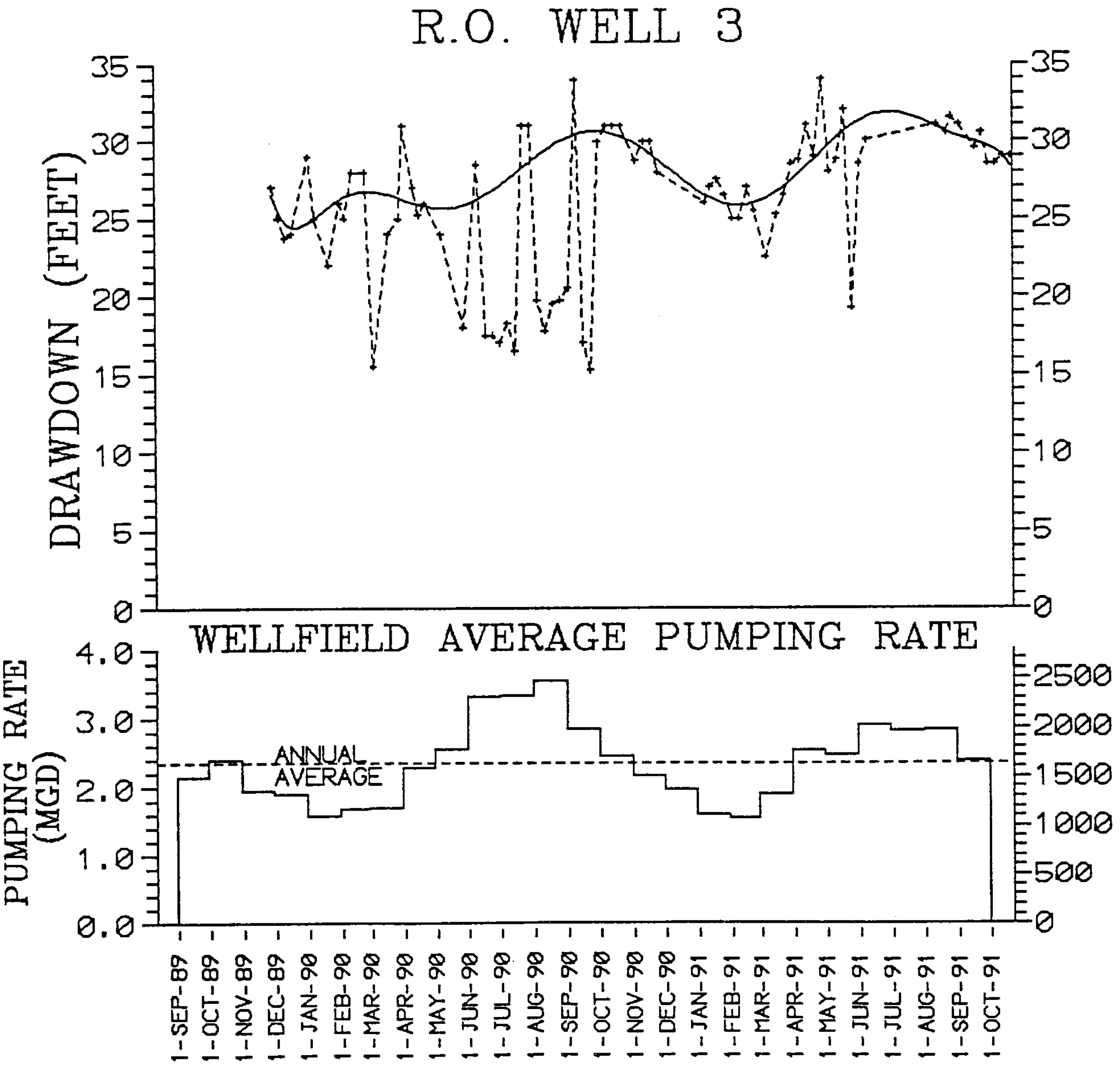

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FIGURE 4-11. REPORTED R.O. WELL 3 DRAWDOWN AND MONTHLY AVERAGE WELLFIELD PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

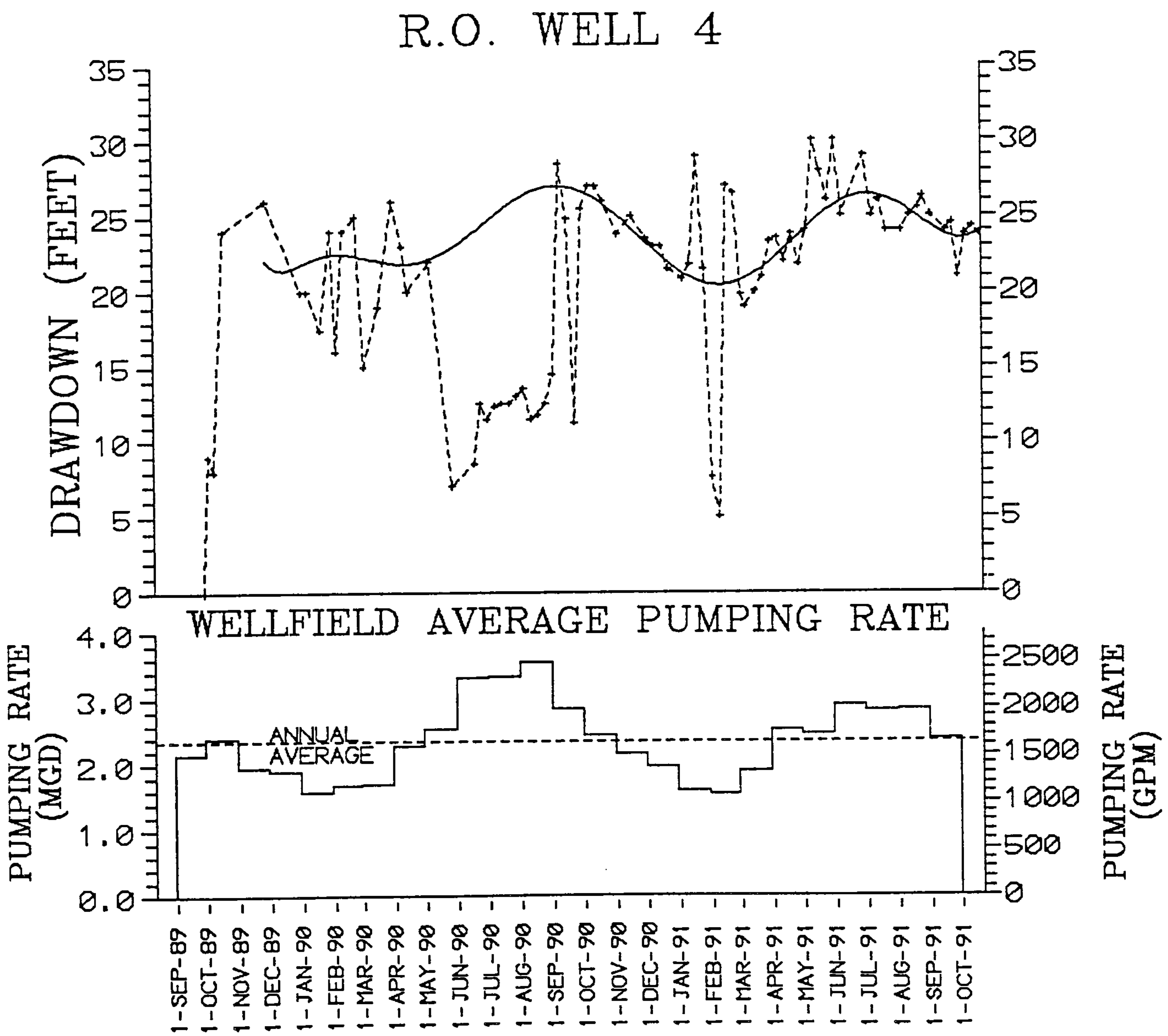

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FIGURE 4-12. REPORTED R.O. WELL 4 DRAWDOWN AND MONTHLY AVERAGE WELLFIELD PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

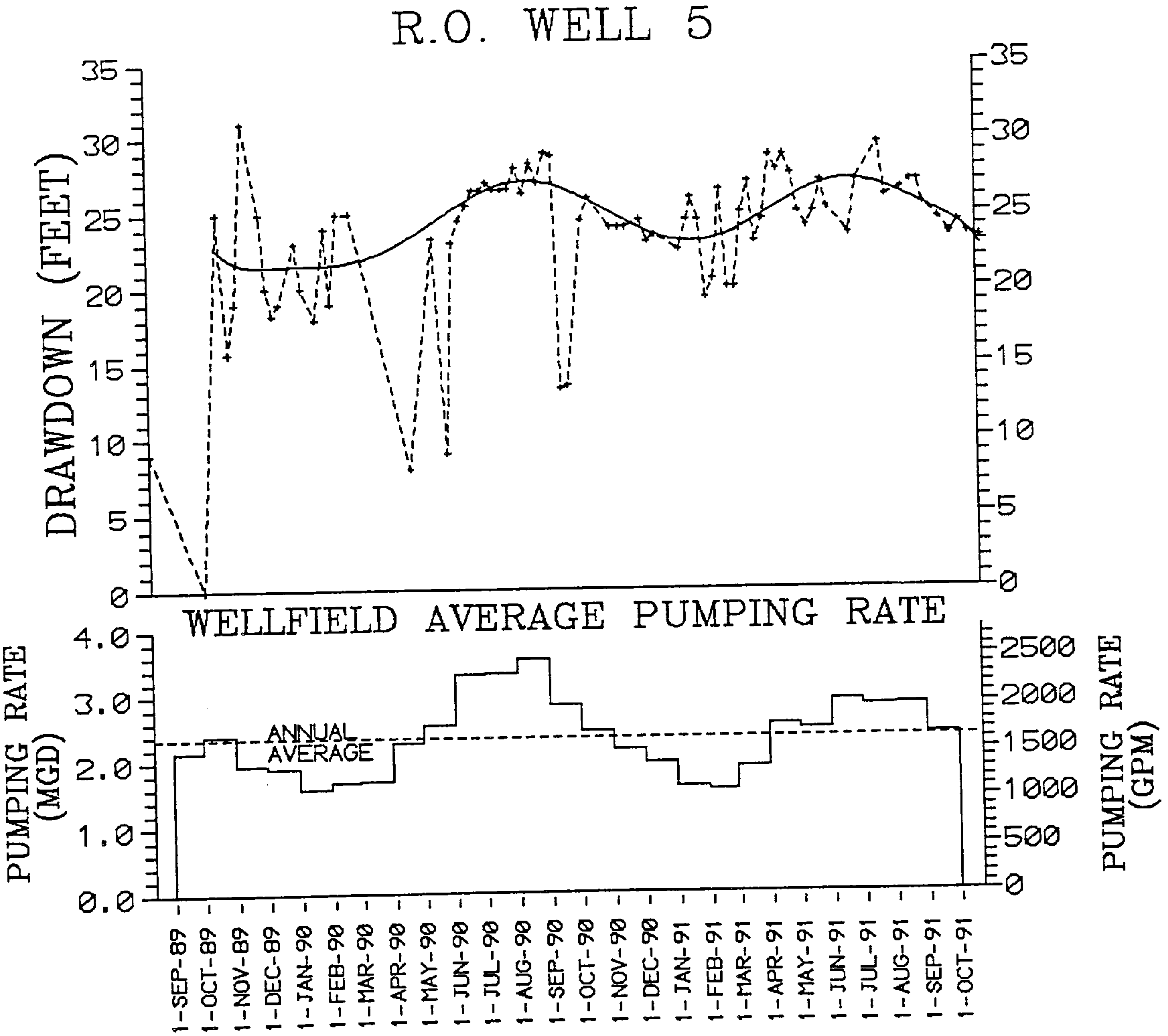

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FIGURE 4-13. REPORTED R.O. WELL 5 DRAWDOWN AND MONTHLY AVERAGE WELLFIELD PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

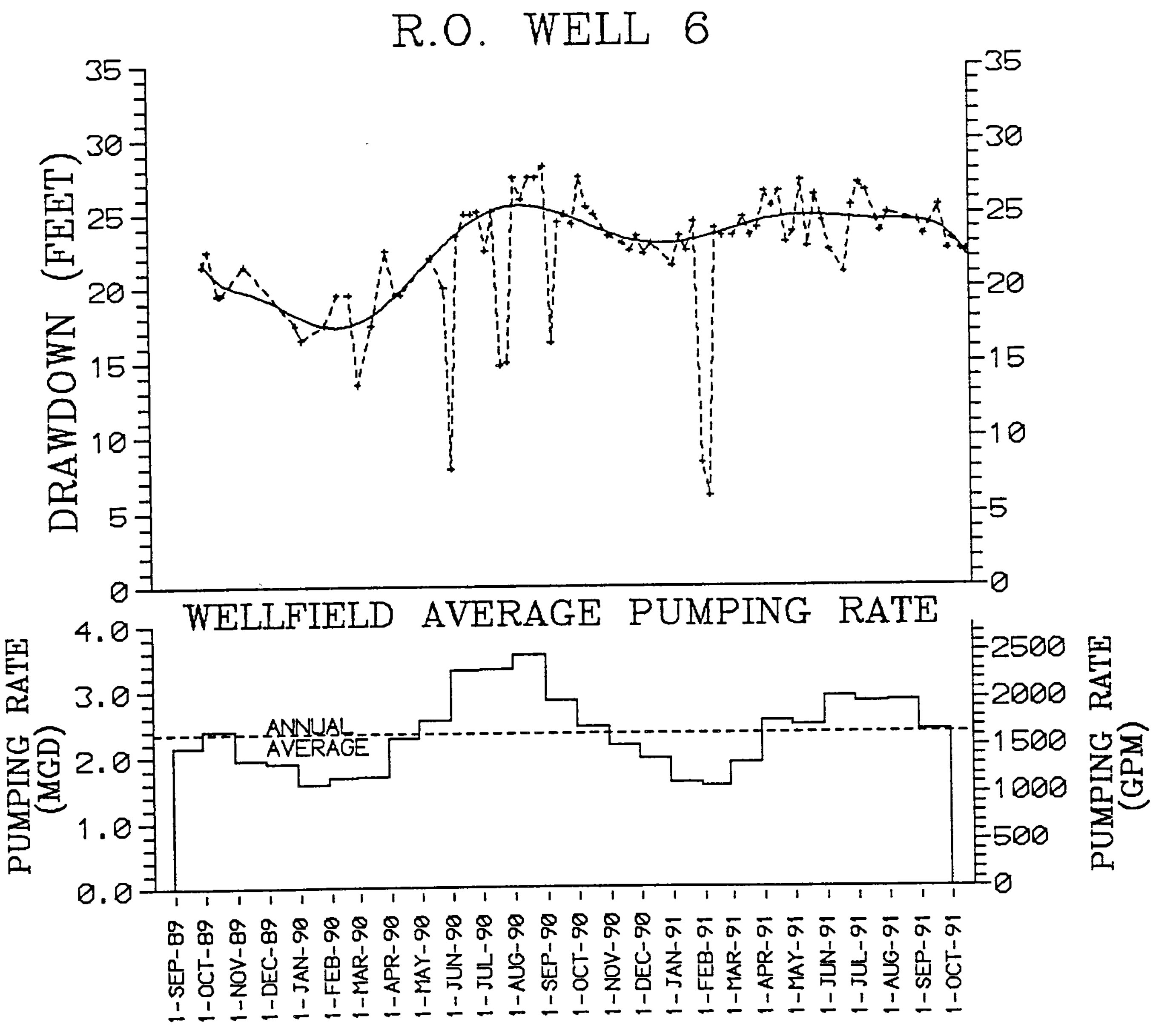

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FIGURE 4-14. REPORTED R.O. WELL 6 DRAWDOWN AND MONTHLY AVERAGE WELLFIELD PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

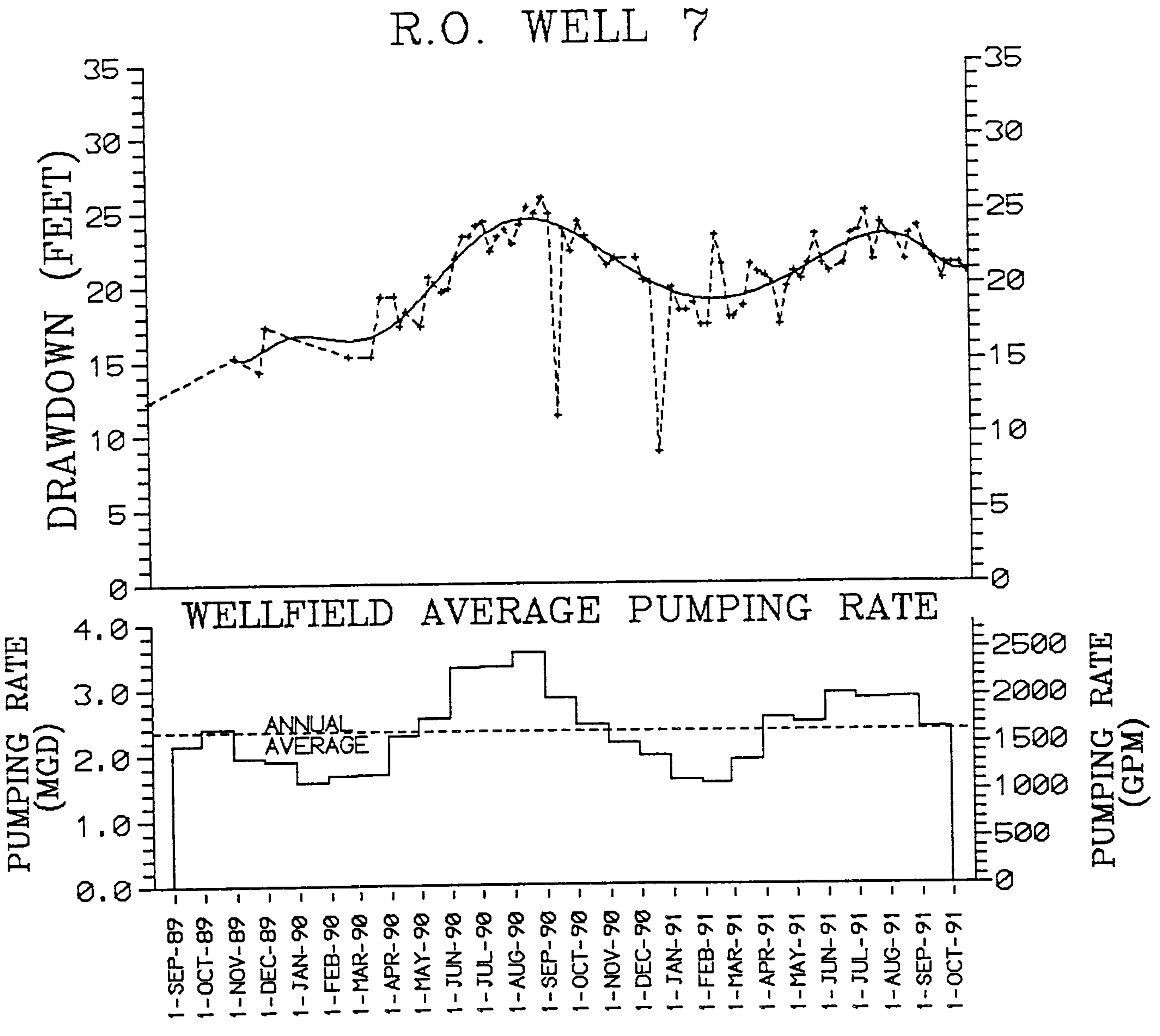

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FIGURE 4-15. REPORTED R.O. WELL 7 DRAWDOWN AND MONTHLY AVERAGE WELLFIELD PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

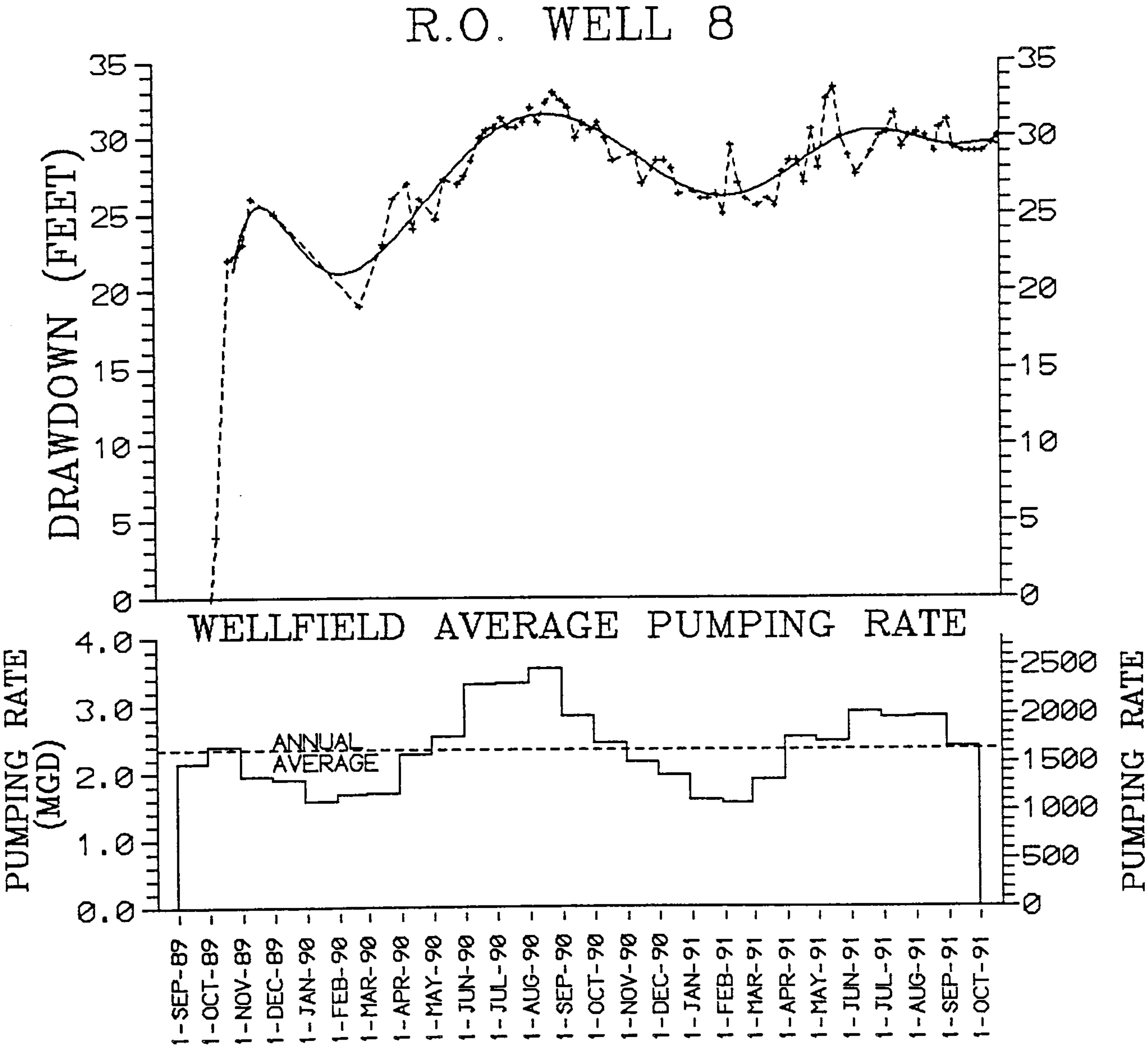

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FIGURE 4-16. REPORTED R.O. WELL 8 DRAWDOWN AND MONTHLY AVERAGE WELLFIELD PUMPING RATE FOR THE PERIOD FROM 9-89 THROUGH 10-91.

Static water levels in the wells change through time for a variety of reasons including: seasonal changes in aquifer potentiometric head; adjacent production well status at the time of measurement; seasonal changes in pumpage at the R.O. supply wellfield; duration of recovery period; and differences in barometric pressure at different times of measurement.

Specific capacity is plotted as a function of pumping rate and through time (Appendix A; Figures A-1 to A-16). The specific capacity for each well changes throughout the year in a manner that correlates to the inverse of the wellfield pumpage rate. When the withdrawal rate is low during winter months the specific capacity is high, and when the withdrawal rate is high during the summer months the specific capacity is low. This relationship demonstrates that some well inefficiencies occur and that the well interactions are substantial. The pervasive interactions between the pumping wells means that the specific capacity values are not fully independent measurements of individual well performance.

If the seasonal variations in specific capacity (caused by changing wellfield pumping rates) are disregarded, the plots show generally flat trends. This indicates that no significant changes in well efficiency have occurred in the supply wells during two years of pumping, and the wells are productively stable. The specific capacity determinations are important for indicating relative changes in well performance through time. Therefore, static water levels in the wells should continue to be measured at regular intervals.

Observation Well Water Levels

Of the seven monitor wells in the system, five are screened in the production interval and two are screened in the lower-Yorktown Aquifer. In order to have a constant datum elevation for comparative analysis, all drawdown values used in this report were determined using only one static water level throughout the period of record.

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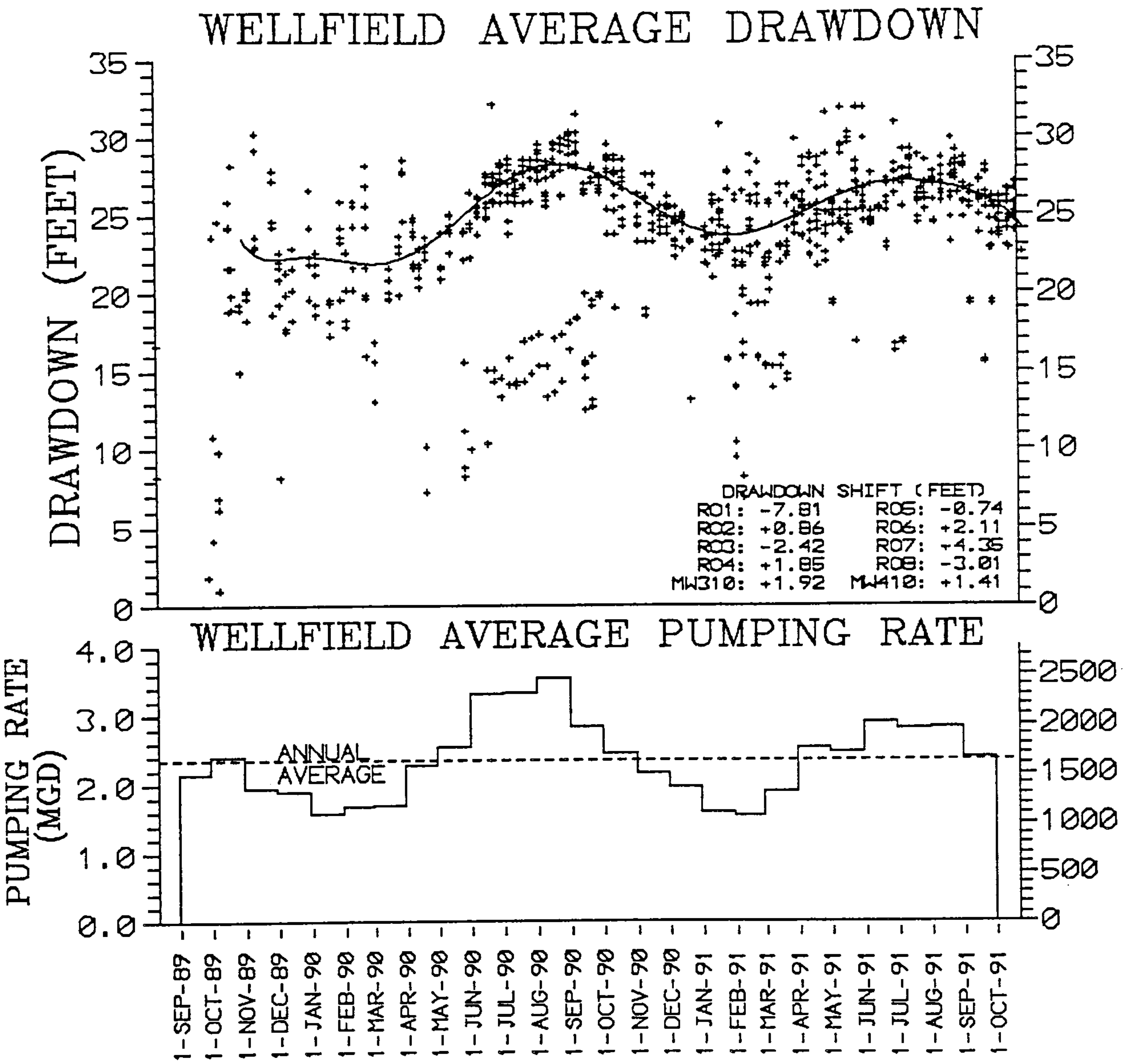

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FIGURE 4-17. AVERAGE REPORTED WELLFIELD DRAWDOWN AND PUMPING RATE FOR ALL WELLS DURING THE PERIOD FROM 9-89 THROUGH 10-91.

Ideally, the datum surface would be the pre-development potentiometric surface, but this information is unavailable. Plots of reported drawdown in the seven monitor wells are given in Figures 4-18 through 4-24.

The drawdown in each monitor well is subject to a considerable amount of weekly oscillation. These variations are attributable to the specific combination of production wells being pumped at the time of measurement, a combination which changes daily. If several supply wells nearest a monitor well are pumping, the drawdown in that well is greater. If wells on the opposite side of the wellfield are pumping, the drawdown in a monitor well will be less. These changes in drawdown can occur with identical wellfield pumpage rates, and this probably generates much of the variation in the data sets. Calculation of moving averages through the data set are used to smooth out much of this variation.

The lack of a common datum elevation for the measuring points on all the wells dictated that the drawdown data be analyzed relative to high and low wellfield pumping rates, rather than the more common method of absolute comparisons of drawdown with pumping rates. Data utilization was limited to comparison of drawdown within an observation well as a function of average wellfield pumpage. This approach increases the importance of accurately determining static water levels; these measurements are difficult because of daily variations in the distribution of wellfield pumpage, and the close proximity of certain observation wells to production wells. While limited in applicability, relative drawdowns in monitor wells did provide some information for model initialization, and for calibration of lower-Yorktown hydraulic coefficients.

All of the monitor wells demonstrate a sinusoidal response to the changing wellfield pumping rate throughout the year. The uniform curves with a horizontal trend and their correlation to wellfield pumpage indicate that the flow field surrounding the wellfield approximates a state of dynamic-equilibrium. The difference in head

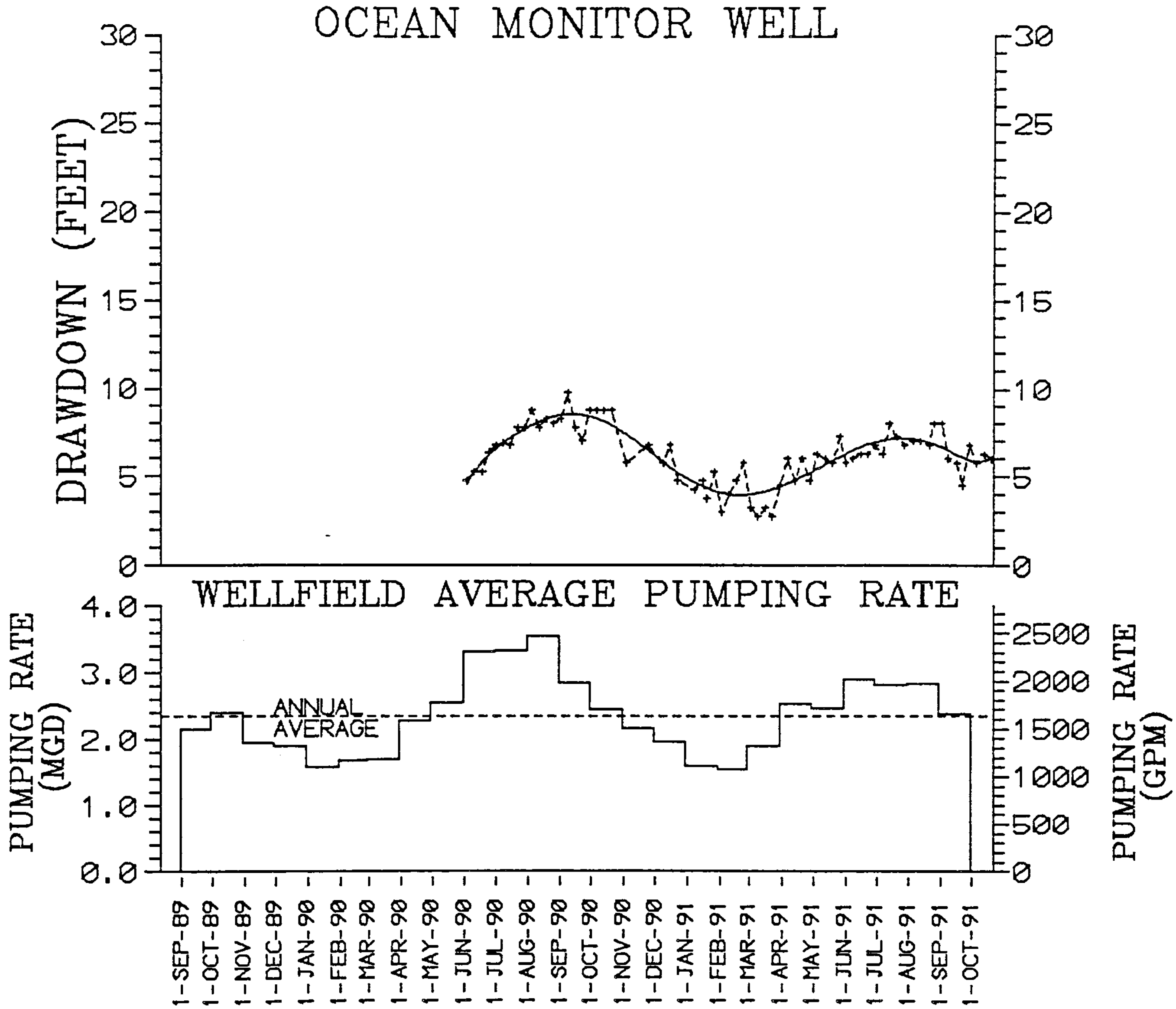

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FIGURE 4-18. REPORTED DRAWDOWN IN THE OCEAN MONITOR WELL FOR THE PERIOD FROM 9-89 THROUGH 10-91.

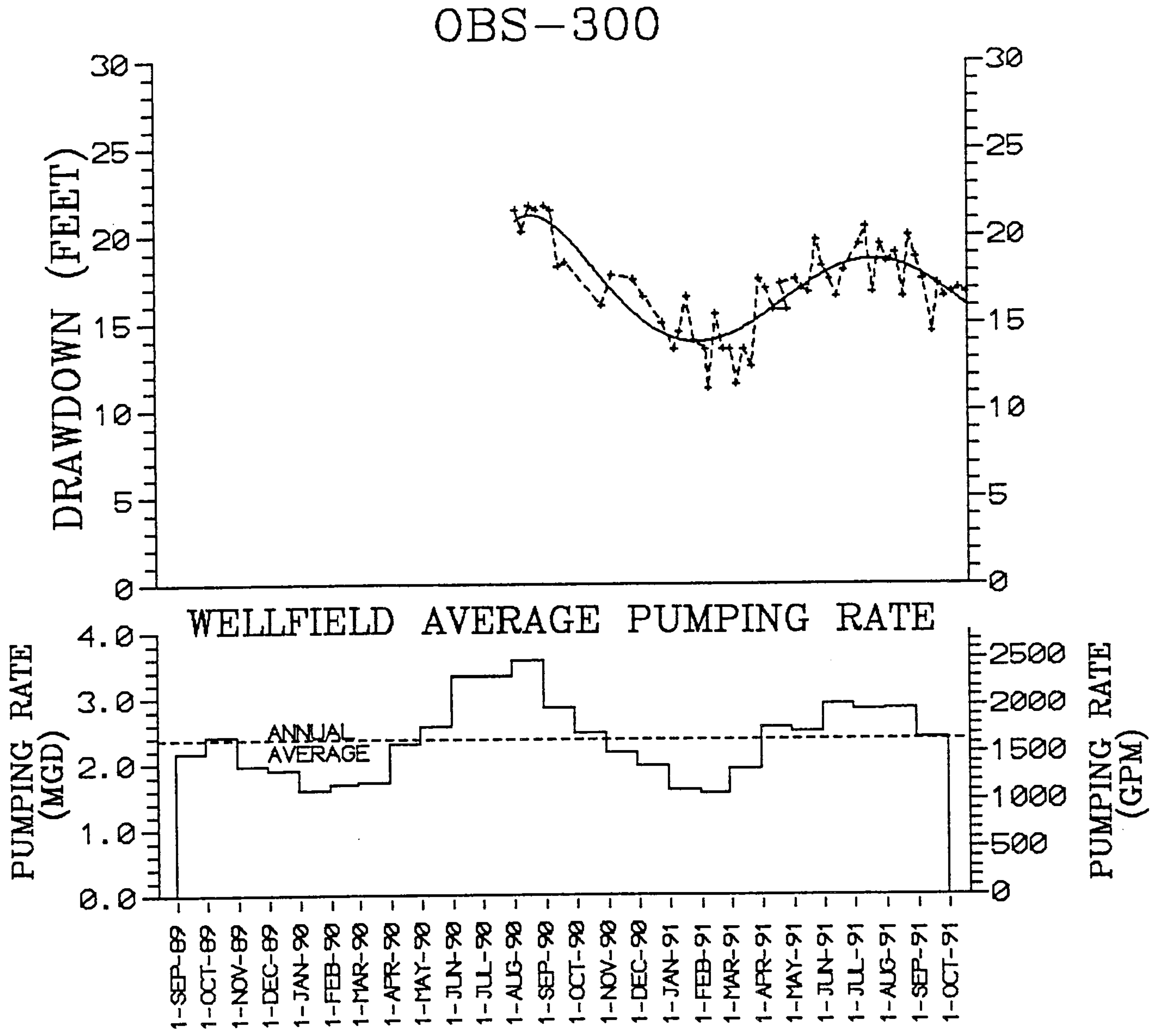

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FIGURE 4-19. REPORTED DRAWDOWN IN MONITOR WELL OBS-300 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

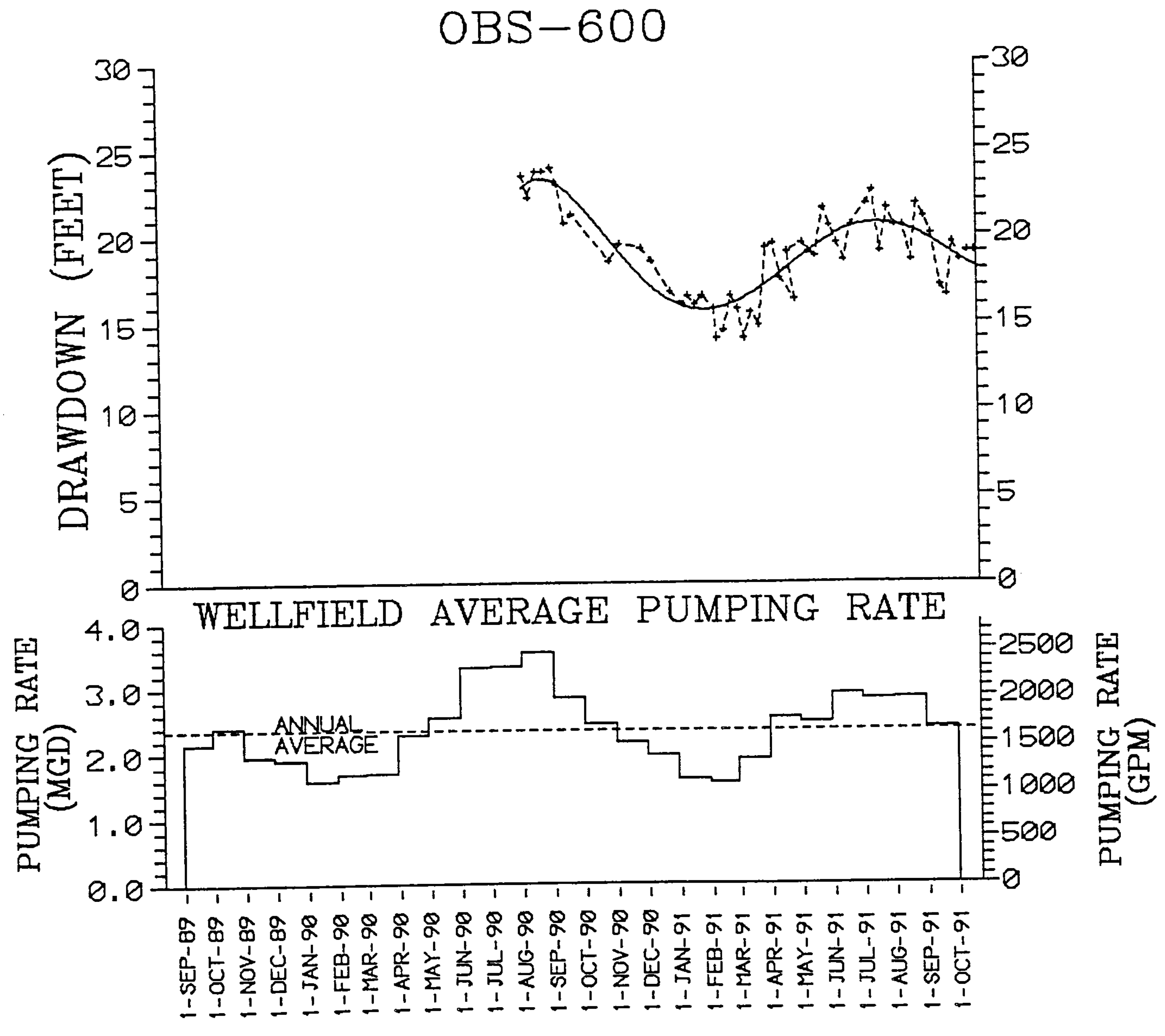

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FIGURE 4-20. REPORTED DRAWDOWN IN MONITOR WELL OBS-600 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

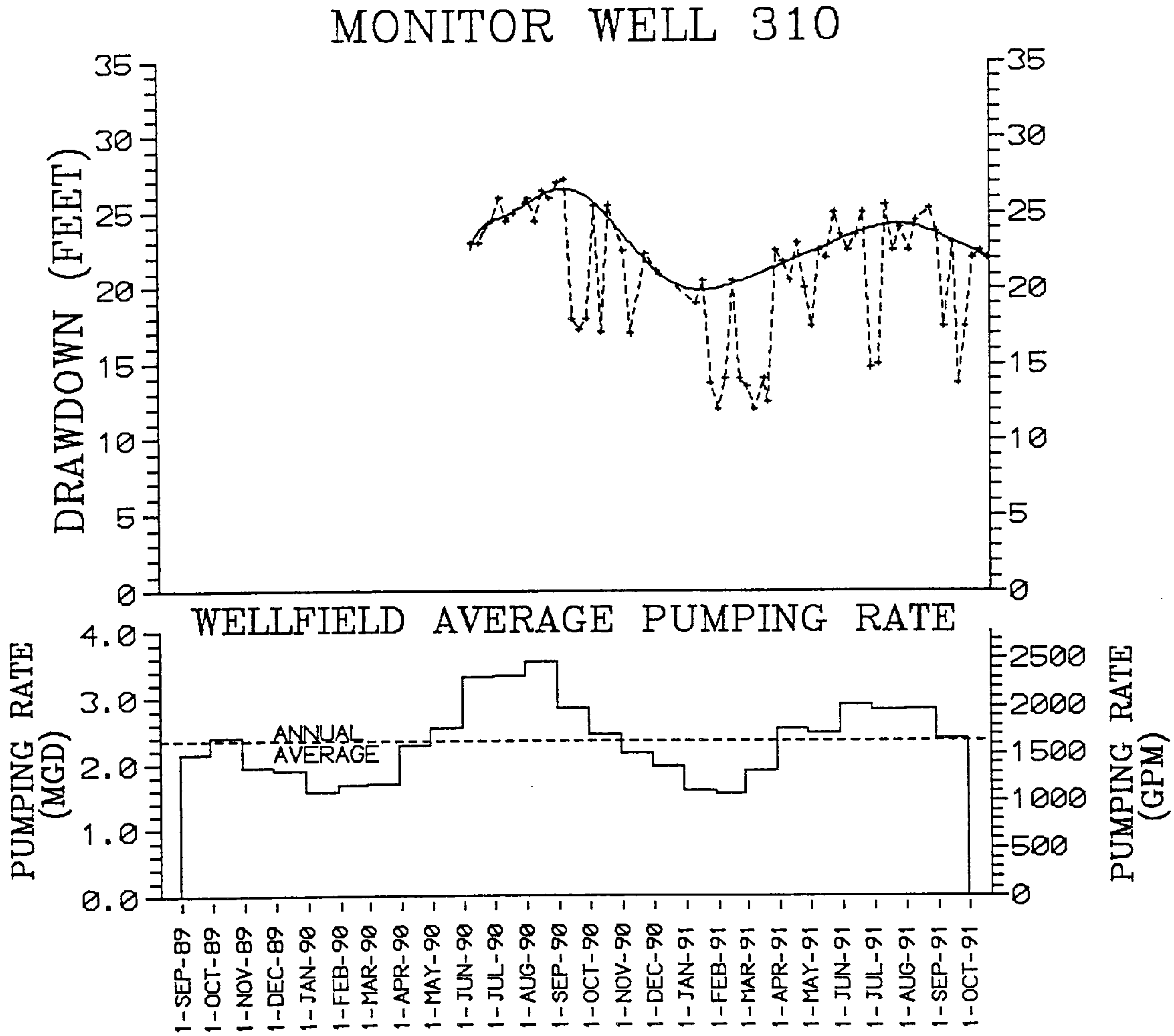

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FIGURE 4-21. REPORTED DRAWDOWN IN MONITOR WELL MW-310 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

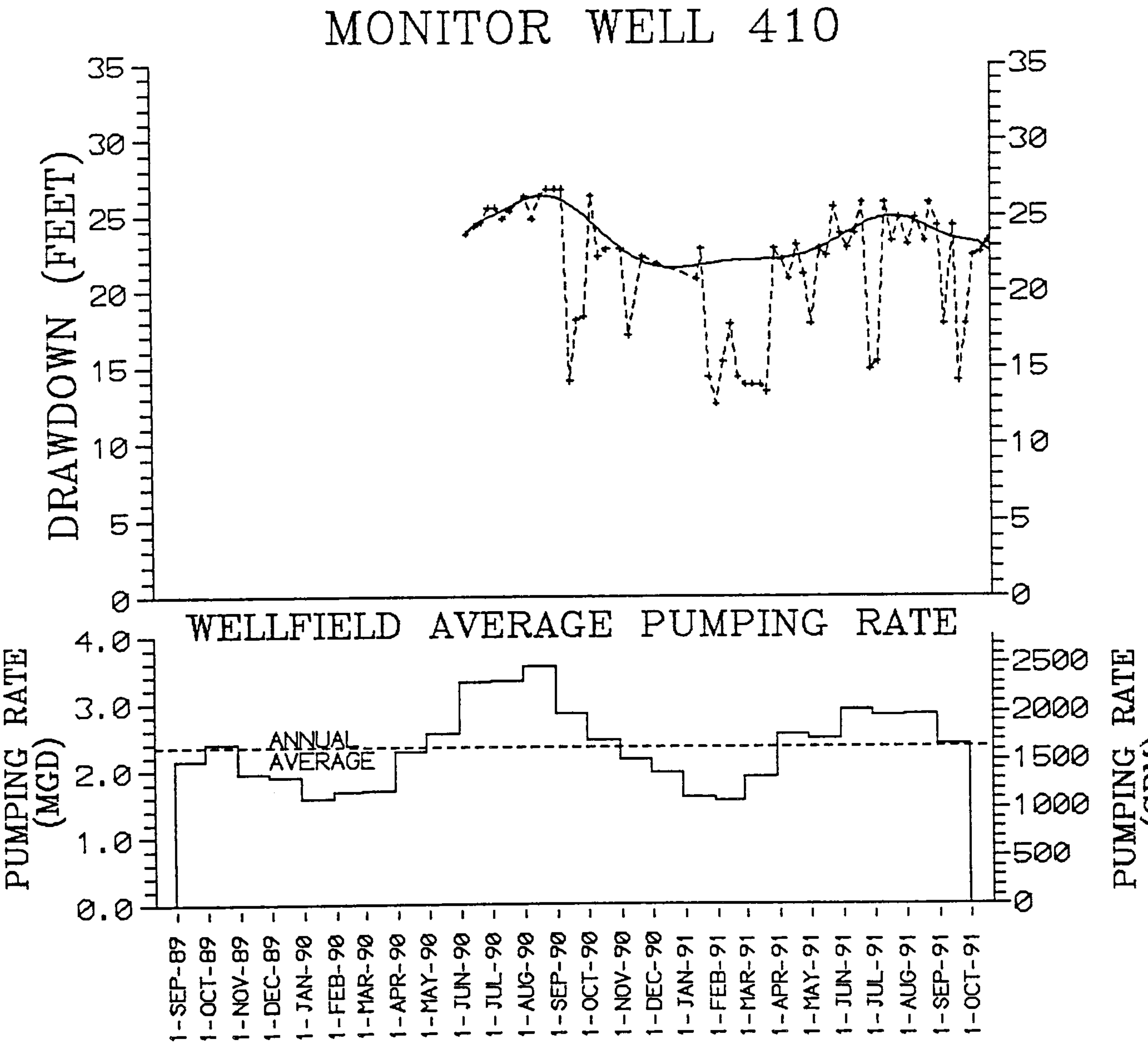

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FIGURE 4-22. REPORTED DRAWDOWN IN MONITOR WELL MW-410 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

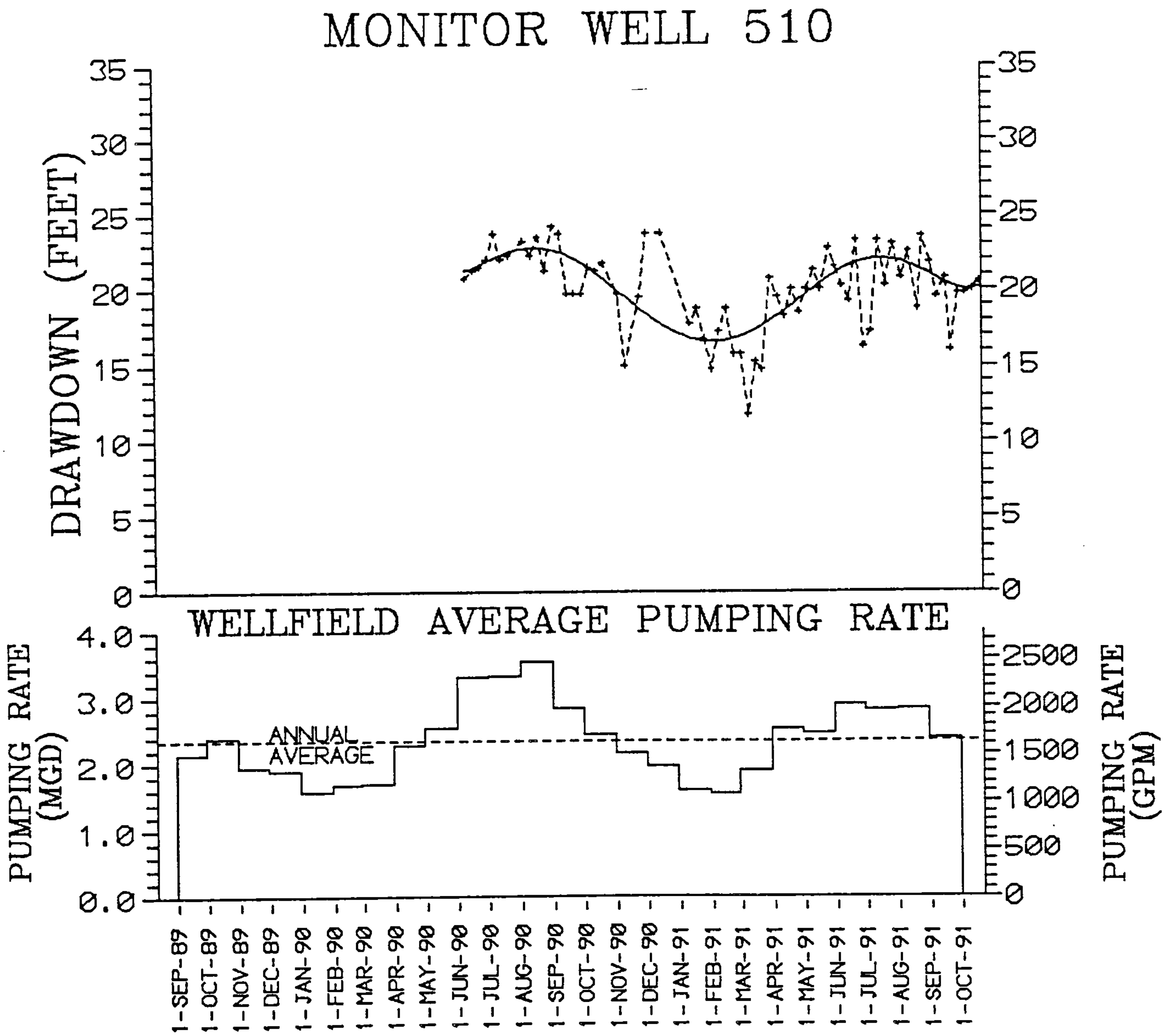

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FIGURE 4-23. REPORTED DRAWDOWN IN MONITOR WELL MW-510 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

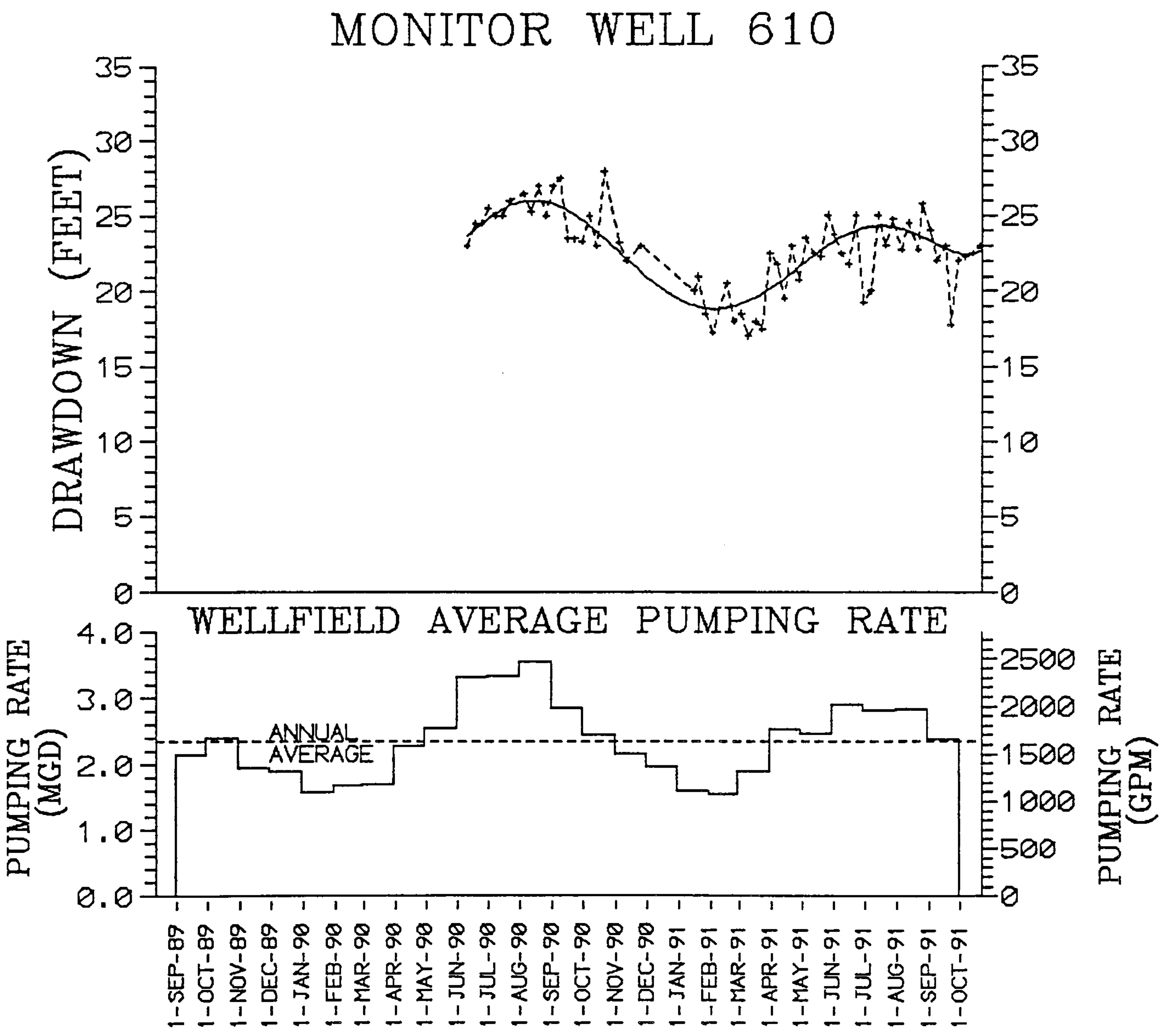

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FIGURE 4-24. REPORTED DRAWDOWN IN MONITOR WELL MW-610 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

between maximum and minimum drawdown in a given well corresponds to the summer and winter extremes of potable demand. These differences are used to calibrate the wellfield flow model in steady-state mode. The maximum and minimum drawdowns for each monitor well are given in Table 4-2.

Total Dissolved Solids in Supply Wells

During two years of pumpage, TDS concentrations in all eight production wells have risen from an average concentration of 1970 mg/l in August, 1989, to 3120 mg/l in October, 1991. The average rate of increase in TDS concentration during this period was 1.38 mg/l per day. Comparisons of individual well pumping histories with TDS concentration changes in each well reveals a good correlation between monthly withdrawal volume and the rate of TDS concentration increase. Monthly average pumping rate and TDS concentration for each supply well are plotted in Figures 4-1 to 4-8. Five-point moving averages are used to plot the TDS concentration line to clarify the general trends in the data. The raw data are plotted as individual data points. Anomalously high and low outlier points were not included in the moving average calculation.

Some wells exhibit a very good relationship between their monthly average pumpage rate and their TDS concentration change. During months with heavy pumpage the rate of increase in TDS concentration is at a maximum in these wells. Following a period of heavy withdrawals from an individual well, the slope of the TDS versus time line drops to zero, indicating no change in concentration. Six of the eight wells exhibit an improvement in water quality when withdrawals were rapidly reduced after the peak demand months in the summer of 1990. The water quality response of individual wells is a function of both the total wellfield withdrawal rate, and the individual well cumulative withdrawal. The wells which are nearest to the wellfield center exhibit the greatest sensitivity to TDS concentration increases.

Linear interpolations of TDS concentrations were calculated to obtain values for all

TABLE 4-2. Monitor well drawdown maxima and minima for the period of record (August 14, 1989, to October 23, 1991), in feet.

MONITOR WELL	MAXIMUM[A] DRAWDOWN	MINIMUM[B] DRAWDOWN	SEASONAL WATER LEVEL DIFFERENCE
OCEAN MW	8.19	4.37	3.82
OBS-300	21.25	13.44	7.81
OBS-600	23.31	15.19	8.12
MW-310	25.75	15.12	10.63
MW-410	26.09	15.03	11.06
MW-510	22.56	16.62	5.94
MW-610	25.90	18.60	7.31

[A] Average of four measurements made in August, 1990.

[B] Average of four measurements made in February, 1991.

eight wells on 7 day intervals through the 800 day period of record. These TDS values were averaged, and a five value moving average operator was applied to smooth the values. This results in a grand average wellfield TDS concentration from which anomalous data points were omitted. The average TDS plot is shown in Figure 4-25, together with a linear best fit which indicates a TDS increase rate of 1.38 mg/l per day. Cumulative wellfield pumpage is plotted below the TDS concentration plot for comparative purposes.

Total Dissolved Solids in Monitor Wells

TDS concentrations in the Ocean Monitor Well on Ocean Bay Blvd. have not changed during the period of record (Figure 4-26). This is strong evidence that the TDS changes observed in the production wells are not the result of lateral encroachment of a saline water front. This well has a fully penetrating screen, however, and should be purged prior to sampling to obtain a sample which is representative of the entire production zone. Density stratification in the well could cause under-estimations of the TDS concentration if the well is not purged and the sample is collected from the top of the casing.

Water qualities in the four monitor wells clustered at the site of R.O. Well 1 clearly reveal the source of the higher salinity water entering the production zone. MW-310 has a ten foot long screen at the top of the production zone, and it exhibits no change in TDS concentration through time (Figure 4-27). This indicates that the TDS changes observed in the production wells are not the result of leakage from overlying zones of higher salinity.

The TDS concentrations in MW-410, screened across 10 vertical feet from 400 to 410 feet BLS near the bottom of the production zone, indicate a very rapid rise during the first two years of pumpage (Figure 4-28). The initial concentration in MW-410 was 2490 mg/l, as indicated on the graph. The first eight water samples collected in this well apparently sampled relatively fresh water in the casing. A new

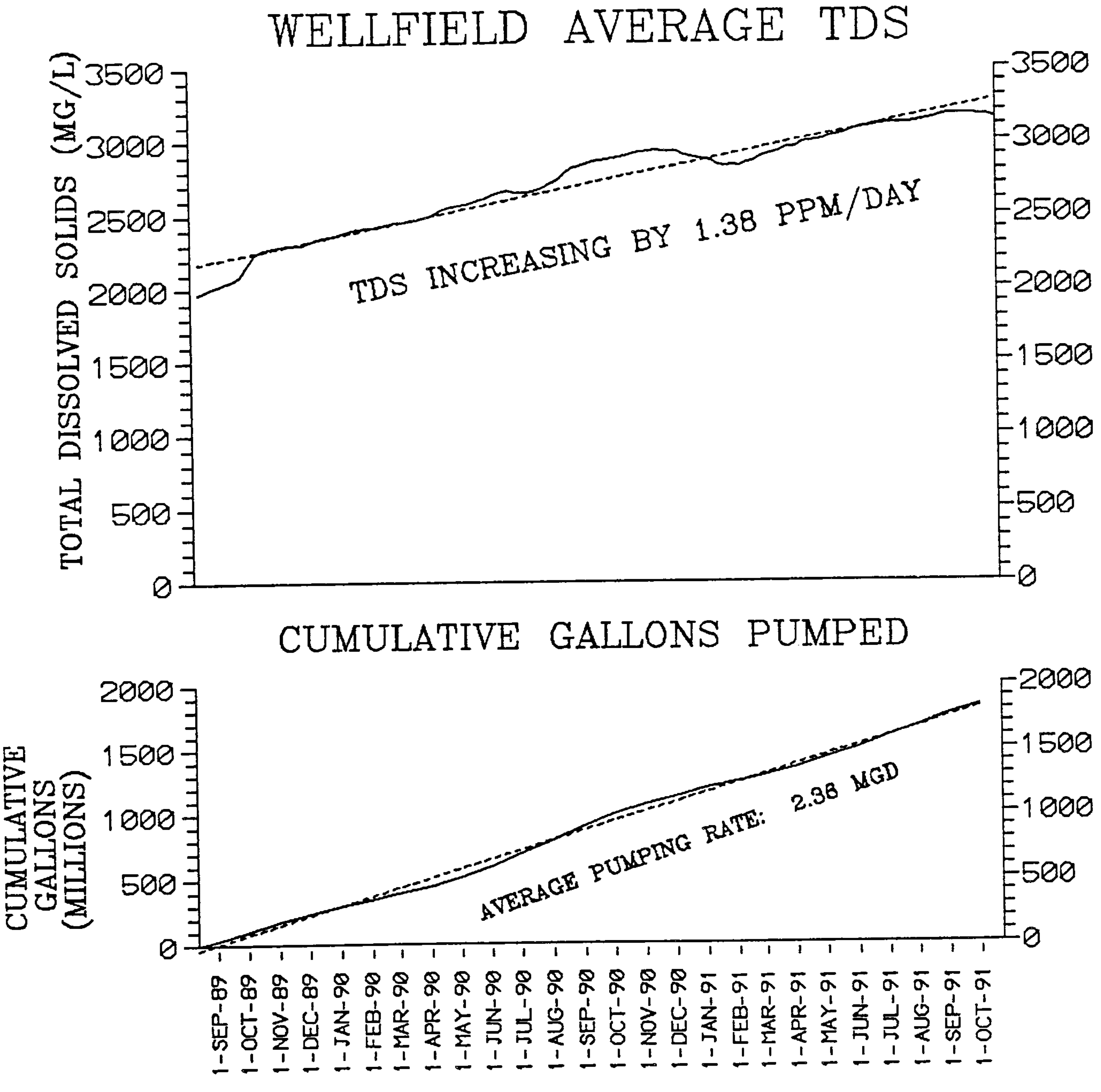

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FIGURE 4-25. AVERAGE WELLFIELD TOTAL DISSOLVED SOLIDS CONCENTRATION AND CUMULATIVE GALLONS PUMPED THROUGH TIME FOR THE PERIOD FROM 9-89 THROUGH 10-91.

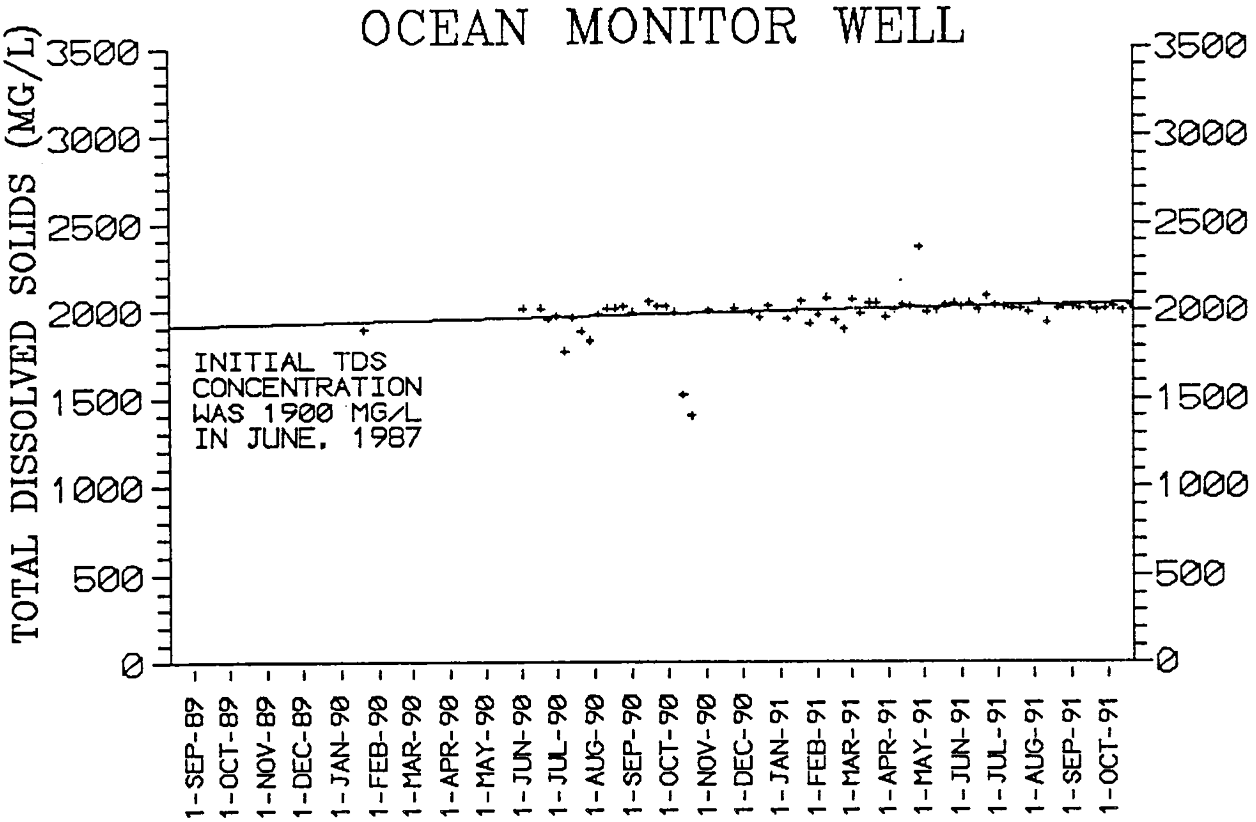

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FIGURE 4-26. MEASURED TOTAL DISSOLVED SOLIDS CONCENTRATION IN THE OCEAN MONITOR WELL FOR THE PERIOD FROM 9-89 THROUGH 10-91.

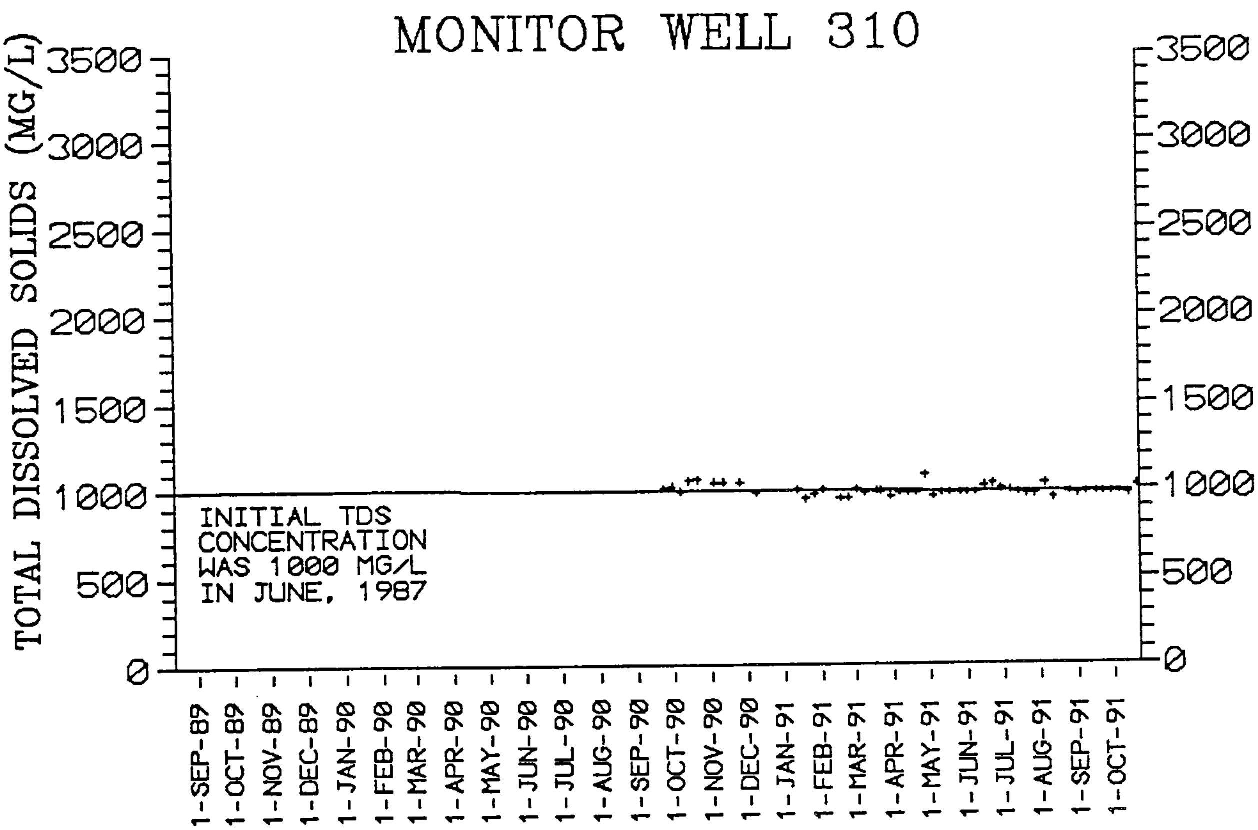

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FIGURE 4-27. MEASURED TOTAL DISSOLVED SOLIDS CONCENTRATION IN MONITOR WELL MW-310 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

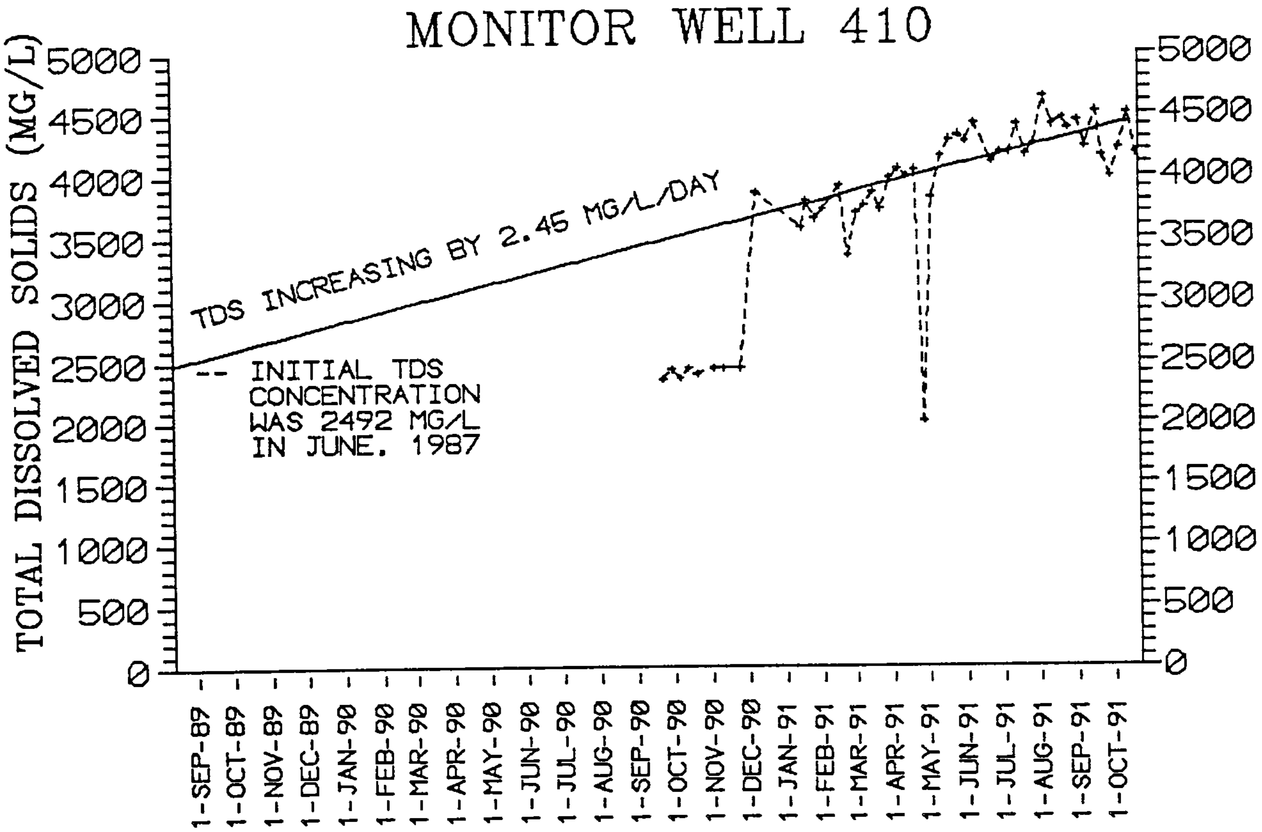

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FIGURE 4-28. MEASURED TOTAL DISSOLVED SOLIDS CONCENTRATION IN MONITOR WELL MW-410 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

sampling technique was used to more effectively purge the well casings in november of 1990, and all subsequent samples show a steady increase in TDS concentrations. A very good linear fit can be made between the initial concentration in 1987, and the concentrations recorded after the well volume was purged during 1991. The slope of this linear fit is 2.45 mg/l per day, substantially higher than the wellfield average of 1.38 mg/l per day. This difference is probably due to dilution across the screened interval of the production wells, with relatively fresh water in the upper portion of the production zone mixing with the higher salinity leakage water at the bottom of the production zone.

Monitor well MW-510 is screened approximately 70 feet below the production zone, from 495 to 505 feet BLS, at the base of the mid-Yorktown Aquitard. A purging history similar to that in MW-410 has occurred in this well, and the first 10 samples collected in 1990 underestimated the true TDS concentrations (Figure 4-29). The initial TDS measurement was 6620 mg/l in June, 1987. A linear fit with the TDS values obtained after December, 1990, is very straight, with a slope of 4.44 mg/l per day. The greater rate of increase in MW-510 relative to MW-410 is due to the much higher TDS concentrations occurring in the lower-Yorktown sediments.

Monitor well MW-610 is screened from 600 to 610 feet BLS, near the base of the lower-Yorktown formation. The TDS concentration in this well was 12,690 mg/l in 1987. Sampling in 1990 and 1991 indicate a range of values suggestive of natural background variations in water quality (Figure 4-30). Some sampling and/or analytical error may contribute to the variations in the TDS values. A linear fit between the initial concentration and all recently measured concentrations does indicate a slight positive slope, amounting to 1.28 mg/l per day.

In summary, the monitor wells indicate that: 1) little or no water is leaking downward through the Yorktown confining beds; 2) substantial upward vertical leakage is occurring across the mid-Yorktown aquitard, transmitting to the

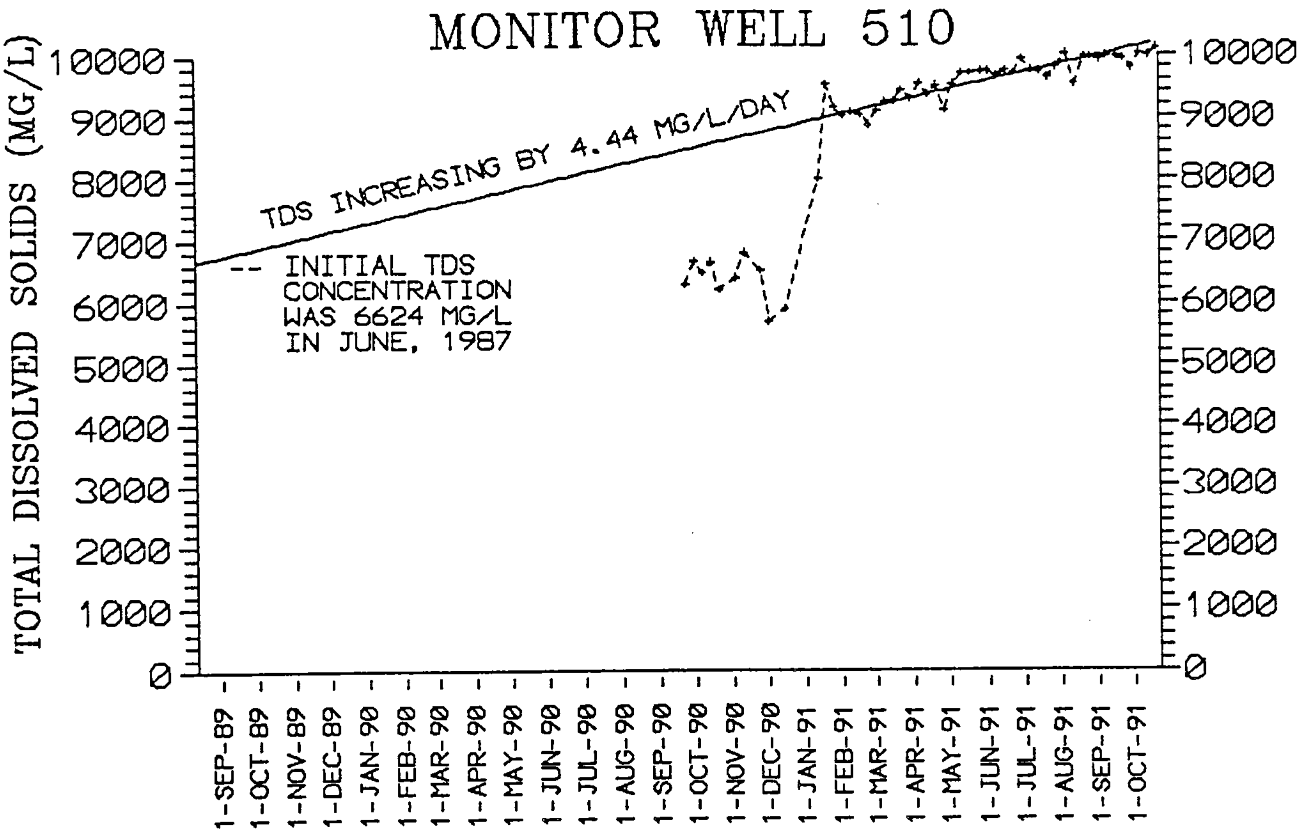

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FIGURE 4-29. MEASURED TOTAL DISSOLVED SOLIDS CONCENTRATION IN MONITOR WELL MW-510 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

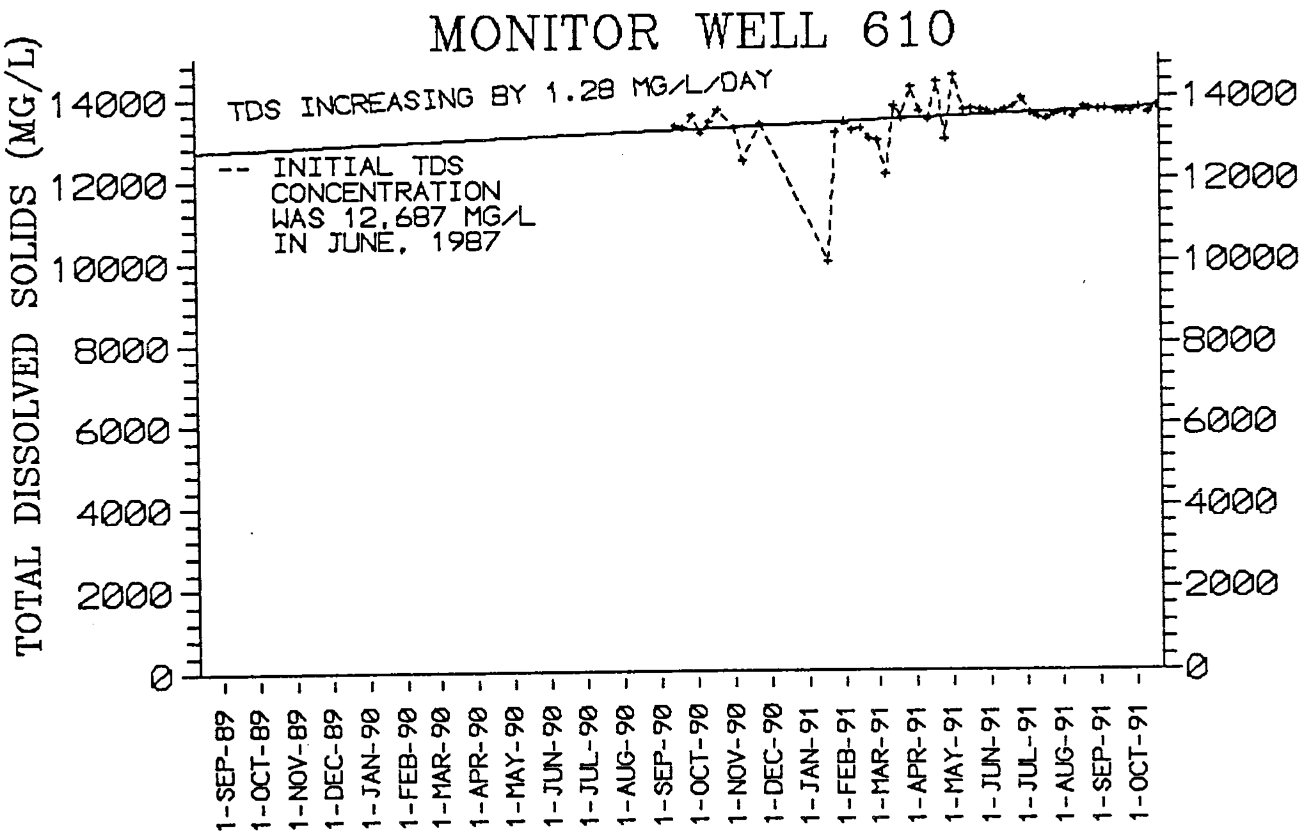

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FIGURE 4-30. MEASURED TOTAL DISSOLVED SOLIDS CONCENTRATION IN MONITOR WELL MW-610 FOR THE PERIOD FROM 9-89 THROUGH 10-91.

production zone water with elevated TDS concentrations; 3) upward vertical leakage is occurring from the lower half of the lower-Yorktown Aquifer to the transmissive sand layer at the top of the lower-Yorktown Aquifer, bringing in high salinity water; and 4) possibly some water is leaking upwards through the underlying Pungo River Formation confining beds, but this is not as clearly supported. Water quality degradation in the mid-Yorktown Aquifer appears to be primarily caused by upward leakage of water with high TDS concentrations from the strata composing the lower sections of the Yorktown Formation. This evidence supports a conceptual model of the Yorktown Aquifer which precludes leakage from the over- and underlying confining beds.

V. GROUNDWATER MODELING

Objectives

The objectives of the groundwater modeling effort were to: 1) develop a flow model which is calibrated to the measured aquifer hydraulic parameters and observed flow-field characteristics; 2) develop a solute transport model which is calibrated to the observed changes in water quality through time; 3) use the flow and solute transport calibrated model to estimate the future changes in water quality in the primary wellfield; 4) use the model to predict the probable water quality in a new wellfield with a different well site configuration.

Groundwater modeling is a methodology which permits a quantitative analysis of groundwater systems. The changes in total dissolved solids concentrations in the Baum Tract wellfield were simulated by constructing and validating a numerical model. Numerical modeling aids in interpretation of the hydrogeologic data describing the aquifer system. Once calibrated, the model can be used in predictive mode for analyzing the Yorktown Aquifer response to changes in withdrawal rates and to new well site configurations and pumping schedules. The modeling process provides quantitative indicators for guiding resource management policy.

Data Availability

The design of a three-dimensional groundwater model depends on the availability of aquifer hydraulic parameters at different locations in the groundwater system. Controlled condition aquifer tests performed on the Yorktown Aquifer provide excellent data relating to aquifer response in the range of one to forty days. Observation well data collected during two years of wellfield withdrawals indicate the quasi-equilibrium hydraulic response of the aquifer, which was then compared to the known pumping rate variations to establish realistic model boundary conditions.

Aquifer tests in the Yorktown Aquifer in the vicinity of the Outer Banks are limited to two tests at Kill Devil Hills prior to the wellfield start-up, and one at Rodanthe. The parameters determined at these locations indicate good lateral continuity of aquifer properties between Kill Devil Hills and Rodanthe. No aquifer tests have been conducted in the deeper portions of the Yorktown Aquifer, from 420 below land surface to its lower boundary with the Pungo River confining unit at 660 feet below land surface. Two monitor wells are in place which tap this zone, but determination of the lower-Yorktown Aquifer hydraulics from the water level data from these two wells is difficult. At this time, the transmissivity of the lower-Yorktown Aquifer is unknown. The vertical leakance parameters for these lower intervals are also unknown.

Potentiometric surface data for the Yorktown Aquifer which is usable in the model is limited to water levels measured in the Ocean monitor well, and OBS-300 and OBS-600. These are the only monitor wells located at a distance from any supply well. The pumping level data collected in the supply wells cannot be used for general potentiometric surface analysis due the variables associated with near-bore hole turbulence and well efficiency, and the four monitor well cluster at R.O. Well 1 are each affected by the steep drawdown cone surrounding the production well.

Water level measurements are taken from the cluster monitor wells when R.O. Well 1 is both actively pumping and when it is in turned off in stand-by status. Although the temporal variables associated with rotation of pumping among the eight supply wells makes analysis of these data difficult, the difference in quasi-equilibrium water levels in these wells, between summer maximum and winter minimum pumping rates, is usable to initialize and calibrate the modeled hydraulic coefficients of the Yorktown Formation sediments in the vicinity of the wellfield.

Very few data on Yorktown Aquifer hydraulics in the Outer Banks area are available other than the several pump tests previously mentioned. Regional groundwater modeling studies (Giese et al., 1991) use values which have been calibrated on a very broad scale, regional basis, and are not applicable to the site specific nature of the present study. There is a need for additional hydraulic information from the lower-Yorktown, but as this interval is currently not a viable water resource due to its high salinity, it has very few test wells from which to collect such information.

Monitor wells MW-510 and MW-610 in the well cluster installed at R.O. Well 1 provide excellent water quality data for the lower-Yorktown Aquifer, but only limited information on lower-Yorktown Aquifer hydraulic response. As previously discussed, the water level data from these wells is inconclusive with regards to relative heads, hence the vertical gradient in the lower-Yorktown Aquifer remains difficult to ascertain.

Transmissivity and leakance values for the lower-Yorktown Aquifer are necessary for refining the hydraulic model, and to aid in understanding the magnitude of the saline-water upconing threat. Aquifer performance tests in the lower-Yorktown horizons would require at least two additional monitor wells into this zone, located within approximately 500 to 1000 feet of MW-510 and MW-610. A carefully executed pump test using R.O. Well 1 and monitor wells MW-510, MW-610, and the additional deep monitor wells, would assist in the determination of the leakance across these layers and transmissivity for the lower-Yorktown Aquifer. An additional monitor well, screened in the Pungo River confining beds, would help determine the degree, if any, of upward leakage into the lower-Yorktown Aquifer. This would help indicate the degree of confinement below the Yorktown Formation, and would increase the reliability of long-term water quality projections.

VI. MODEL SELECTION AND CONSTRUCTION

Model Selection

The U.S. Geological Survey Modular Three-dimensional Finite-Difference Groundwater Flow Model (MODFLOW; McDonald & Harbaugh, 1988) was used to simulate the three-dimensional flow field in the Yorktown Aquifer system beneath Kill Devil Hills during the calibration of phase of modeling. This model is widely used for unconfined and confined flow modeling, and is much more computationally efficient than the more numerically intensive solute transport models.

To reproduce the observed changes in total dissolved solids in the supply wells, simulation of solute transport in three-dimensional space is required. Solute transport in a three dimensional flow field requires a model with facilities to accommodate multiple layer geometry, variable grid spacing in the x and y axis, as well as solute concentration tracking algorithms. Widely used models which accommodate these requirements include SWIFT III (U.S. NUREG/CR-1968), HST3D (U.S. Geological Survey), and FTWORK (Faust, et al, 1990). SWIFT III and HST3D can be operated in fully coupled mode, in which density, viscosity, solute concentration, and hydraulic flow equations are solved simultaneously. FTWORK solves the hydraulic and solute concentration equations separately.

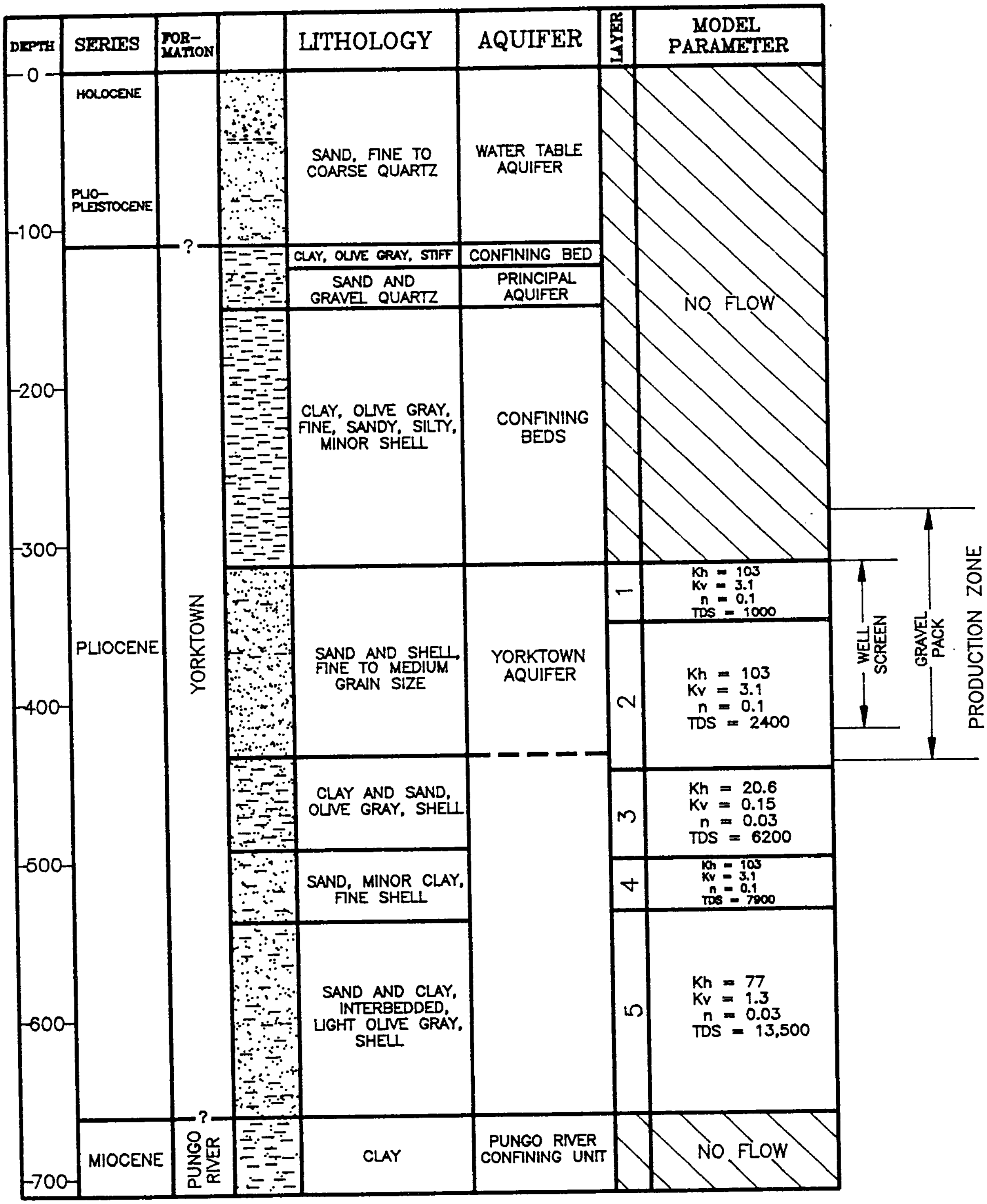
Early calibration runs were made using both the SWIFT III transport code and the FTWORK transport code. No appreciable difference in net upconing was observed between the fully coupled SWIFT code and the uncoupled FTWORK model. Given the degree of uncertainty regarding leakance values for the mid-Yorktown aquitard, the influence of density drives becomes insignificant. This finding is due to the large vertical hydraulic gradients in the vicinity of the wellfield, which are very much larger than the density gradients caused by salinity differences between mid-Yorktown and lower-Yorktown Aquifer waters. The improved computational efficiency of the FTWORK model was considered more advantageous than accommodation of the minor effect of the vertical density differential. This consideration was supported by the assessment of the hydrologic problem as one of upward leakage across thinly bedded clays and sands rather than lateral migration in a thick uniform confined aquifer or vertical migration within an isotropic media. Therefore, the FTWORK model was used for all subsequent calibrations and simulations.

Hydrogeologic Framework

Developing a valid model requires observing nature and posing an accurate model framework for the three dimensional hydrologic system. It entails establishing vertical and lateral boundary conditions, hydraulic parameters for each layer in a multi-layer framework, and calibration of model output to known physical conditions. The multi-layer hydrologic regimes and corresponding model framework are shown in Figure 6-1. Vertical no-flow boundaries are used to represent the thick clay sequences of the overlying, upper Yorktown Formation and the underlying Pungo River Formation. All model water flow is therefore forced to occur within the more permeable sediments of the mid- and lower-Yorktown Formation (Figure 3-1). These sediments are represented by five active model layers.

For initial modeling, the 160,000 gpd/ft transmissivity measured for the mid-Yorktown Aquifer at the Baum Tract was converted into hydraulic conductivity for the 130 foot production thick zone. This hydraulic conductivity was used as a basic unit for hydraulic parameter conceptualization, and assigned an arbitrary qualitative value of 100 points (representing the mid-Yorktown Aquifer). A point system was used to assign the various layers their horizontal and vertical hydraulic conductivities, relative to the 100 points assigned to the primary aquifer, based on detailed lithologic and geophysical interpretation, as no hydraulic parameters have been reliably established for the deeper Yorktown Formation layers.

The 130 foot thick production interval was divided into two layers to accommodate the differing total dissolved solids concentrations observed in MW-310 and MW-410



Legend

Kh = HORIZONTAL HYDRAULIC CONDUCTIVITY (ft/day)
Kv = VERTICAL HYDRAULIC CONDUCTIVITY (ft/day)
n = EFFECTIVE POROSITY
TDS = TOTAL DISSOLVED SOLIDS (mg/l)

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ENVIRONMENTAL AND GROUNDWATER SERVICES

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PROJECT NAME: DARE COUNTY, NORTH CAROLINA NUMBER: CHO-401

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FIGURE 6-1. HYDROGEOLOGIC SECTION OF DARE COUNTY BAUM TRACT WELLFIELD WITH CORRESPONDING MODEL LAYER CONSTRUCTION.

at the top and bottom of this interval. The sandy clay unit occurring at a depth of between 450 and 510 feet was specified as layer three. The thin sand unit lying between 510 and 540 feet was represented by layer four, and the clayey sand unit occurring between 540 feet and 660 feet was accommodated by layer five.

Each layer required specification of horizontal and vertical hydraulic conductivity, effective porosity, water quality, and specific storage. The product of horizontal hydraulic conductivity and layer thickness is layer transmissivity. Vertical hydraulic conductivities were initially established based on literature K_H/K_V ratios. Vertical hydraulic conductivity divided by layer thickness is layer leakance. However, the model uses block-centered nodes to discretize flow field volume, hence layer-to-layer leakance is the reciprocal of the sum of the reciprocals of the half-layer leakances. These leakances are calculated by the program during run-time.

The effective porosity cannot be measured directly without core samples of the aquifer materials, but literature values for typical marine sediments can be used with reasonable confidence to establish initial model conditions. Layers one, two, and four, representing fine to coarse sands, were specified to have an effective porosity of 0.10, or ten percent. Layers three and five, representing clayey sands, were assigned an effective porosity of 0.03, or three percent.

Specific storage is storativity divided by aquifer thickness. The storativity of the mid-Yorktown Aquifer was determined from aquifer performance testing in 1986 and 1987. The storativity determination from a 72-hour pump test in R.O. 1 was 4.0×10^{-4} was used to calibrate a numerical pump test, and the resulting specific storage was 3.2×10^{-5}.

Model Construction

Approximately ten different model grids were used during the process of initial calibration and subsequent solute transport modeling, but one basic grid was used for a majority of both hydraulic calibrations and solute transport simulations. This variably spaced model grid contained 69 columns, 53 rows, and 5 layers, for a total of 18,285 cells (Figure 6-2). The model grid was aligned parallel to the coastline at Kill Devil Hills, and extends 78,940 feet (14.95 miles) in a northeast-southwest direction, and 75,940 feet (14.38 miles) in a northwest-southeast direction. These dimensions place the model boundary cells at a distance of 36,550 feet (6.92 miles) from the nearest R.O. supply well.

It has been assumed that the confining beds above and below the Yorktown Formation are both laterally continuous and unbreached. As is often the case, the true hydraulic boundary conditions are not known, but in this model they are specified to occur as lateral recharge boundaries. The actual boundary conditions of a confined aquifer system are rarely identified with certainty, but the question is scaler in nature. The actual boundary conditions may range from purely lateral recharge, as one extreme, to areal leakage recharge only, on the other extreme.

On the local scale represented by the models used in this report, it is assumed that the boundary conditions occur as lateral recharge only. Prescribed head boundaries were specified for the model grid perimeter along the southwest, southeast, and northeast sides. The boundary to the northwest was specified to consist of standard active cells with a zero-flux boundary condition, simulating the northward lateral facies change in the Yorktown Formation from interbedded sands and sandy clays to thick beds of clay with very low transmissivity. The lateral prescribed-head boundary configuration, excluding the zero-flux boundary to the northwest, supply all the water entering the model system in the steady state flow simulations. This boundary configuration precludes downward or upward vertical leakage from units overlying and underlying the Yorktown Formation. This view of the over- and underlying boundary conditions is supported by water quality data, to a greater extent for the overlying layers, and to a lesser extent the underlying layers. The model also assumes that layer thickness, layer hydraulic conductivity, and inter-

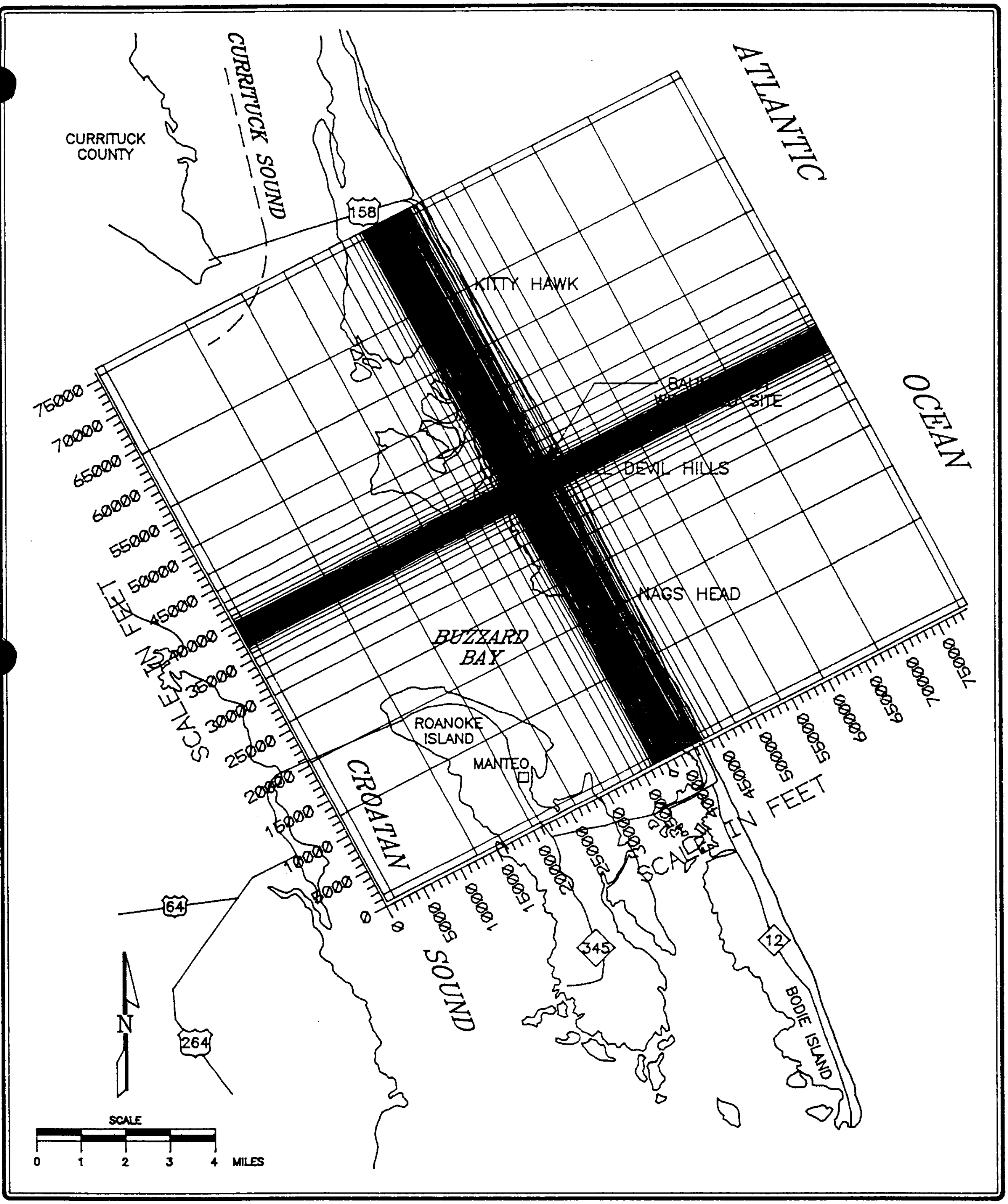

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FIGURE 6-2. MAP SHOWING MODEL GRID LOCATION AND CONSTRUCTION.

layer leakance properties are laterally uniform across the modeled area. The use of five discrete model layers to describe the full 360 foot thickness of the mid- and lower-Yorktown Formation may represent a simplification of the true hydraulic flow field. However, this model design is built upon a reasonable group of assumptions considering the available data.

VII. THREE DIMENSIONAL HYDRAULIC AND SOLUTE TRANSPORT MODELING

Initial Conditions

Initial conditions used in the groundwater model include the initial aquifer parameters and water quality for each layer, as well as the initial potentiometric surface. The aquifer parameters used were based on a relative weighting scheme, proportionalizing each layer with respect to the lithologic log and the observed hydraulic conductivity in the production zone. Literature-derived horizontal to vertical hydraulic conductivity ratios were initially used for the sand units and clayey sand units. The hydraulic parameter weighting scheme used prior to model calibration is summarized in Table 7-1.

The pre-development hydraulic gradient in the Yorktown Aquifer at Kill Devil Hills was less than one foot per mile, with flow generally to the east. Superimposed on the pumping-induced drawdown cone, this subdued regional gradient is unnoticeable. Limitations in the data set forced model calibration to be based on seasonal changes in potentiometric head only. Therefore, the initial Yorktown Aquifer potentiometric surface was specified to be horizontal (all layers with equal head), and all calculated drawdowns are in terms that are relative to the regional gradient. This is a necessary and valid simplification which is justifiable by the principle of superposition. This principle states that the solution to a hydraulic flow problem involving multiple stresses is equal to the sum of the solutions to a set of simpler individual problems. In this case only the regional gradient and the pumping induced drawdown cone are being superimposed. The principle is valid and applicable to groundwater problems that are governed by linear differential equations, such as flow in confined aquifers (Reilly, Franke, and Bennett, 1984)

Boundary Conditions

The accurate definition of boundary conditions is an essential part of conceptualizing and modeling groundwater flow systems. A groundwater model is defined by

TABLE 7-1. Initial hydraulic parameters used prior to model calibration

MODEL LAYER	THICKNESS (FEET)	K_H WEIGHT^A	K_H^{B} (GPD/FT^2)	T^C (GPD/FT)	K_V^{A} WEIGHT	K_V (GPD/FT^2)	K_V/K_H RATIO
1	100	100	965	96500	20	193	5
2	40	100	965	38600	20	193	5
3	50	15	145	7200	1	9.65	15
4	30	85	823	24600	15	145	5.7
5	180	30	289	52100	2	19.3	15

Notes:

K = hydraulic conductivity
K_h = horizontal hydraulic conductivity
K_v = vertical hydraulic conductivity
b = layer thickness
T = transmissivity

[A] Weights are assigned relative to the hydraulic conductivity of the production zone, which is arbitrarily assigned a weight of 100.

[B] Hydraulic conductivity determined from the transmissivity at R.O. Well 1 (T = 135,100 gpd/ft; average of aquifer tests), and the thickness of the mid-Yorktown Aquifer (140 ft; layers 1 and 2).
K = [(135,100 gpd/ft)/(140 ft)] = 965 gpd/ft^2.

[C] Transmissivity is calculated as the product of hydraulic conductivity and layer thickness.

establishing appropriate boundary values and conditions. Numerical solution of the model involves solving the partial differential equations in the flow domain while simultaneously satisfying the specified pumping withdrawal conditions and the boundary conditions. It is important to distinguish between the real world "physical" boundaries of the natural flow system, and the artificial "numerical" boundaries of the flow model. Whenever possible the numerical boundaries are chosen to reflect known hydrologic features which represent physical boundaries in the real world.

In the case of the Yorktown Aquifer at Kill Devil Hills, few wells exist to help define the hydrologic system peripheral to the wellfield itself. The process of hydraulic model calibration had to be based entirely on the response of the flow-field, as observed in three monitor wells, to the variable stresses of seasonal changes in withdrawal rates. The boundary conditions had to be chosen so that they do not cause the model solution to differ substantially from the response that would occur in the real aquifer system. Therefore, lateral boundary conditions were chosen to be Type I Dirchlet boundaries of specified head, in which the potentiometric head at the model perimeter was held constant during flow simulation, acting as a source of recharge to all layers in the aquifer system. The northeast model boundary was specified to be a Type II Neuman boundary, or prescribed-flux type, with a flux of zero (no-flow) to represent the clay lithologies with dominate the Yorktown Aquifer to the northwest. This design is equivalent to postulating that withdrawals from the Baum Tract wellfield do not cause measurable drawdown at a distance of 6.92 miles from the wellfield. Although no wells are monitored at this distance, this is a conservatively large distance which presents a minimum impact on the hydraulics calibration of the model at the wellfield.

The Yorktown Aquifer confining beds above, and the Pungo River confining beds below the Yorktown, are each assigned the status of no-flow boundaries. They remove from the numerical simulation all interaction with the confining beds and aquifers above the mid-Yorktown and below the lower-Yorktown. The TDS versus time data in the monitor well cluster support this design.

Hydraulic Calibration

The initial hydraulic conductivity for the production zone was chosen based on the pump test derived transmissivity values divided by the production zone thickness. Leakances were based on literature values for hydraulic conductivity ratios in various sediment types. These values required substantial modification before a good match between observed and predicted heads was obtained.

The first component of the calibration process consisted of analyzing the heads in the four clustered monitor wells at the site of R.O. Well 1. These four wells have short, ten foot long screens, and are open to the formation at approximately 100 foot vertical spacings. It was expected that the heads in MW-310 and MW-410 would be very similar because their screens intersect the production interval. The deeper monitor wells (MW-510 and MW-610) should exhibit progressively less drawdown with increasing depth as the stream lines refract towards horizontal below the wellfield. The degree to which the heads differed would indicate the vertical head gradient under the wellfield, which would aid in determining the leakance value for the mid-Yorktown aquitard. Summer versus winter drawdowns in the monitor wells were subtracted to yield the seasonal head differences (Table 4-2). As expected, the head differences in the two shallow monitor wells are very similar: 10.63 and 11.06 feet for MW-310 and MW-410, respectively. However, the head differences in the deeper monitor wells are difficult to interpret: 5.94 and 7.31 feet for MW-510 and MW-610, respectively. These data suggest that the deepest monitor well has a better connection to the production interval than MW-510, which is not possible. Therefore, the downward gradient analysis did not help resolve the leakance question. Instead, water level data from the other monitor wells and the observed TDS concentration changes in the wellfield were used to determine a set of leakance values.

Initial flow calibration was performed using U.S. Geological Survey MODFLOW in steady state mode, and two sets of withdrawal conditions. Pumping rates were used which reflect the summer maximum and winter minimum withdrawals, or 3.55 and 1.55 million gallons per day, respectively. Drawdown values for the three fully penetrating observation wells were used as calibration criteria, and the hydraulic parameters were sequentially adjusted until predicted heads matched observed heads. A sensitivity analysis performed on the hydraulic model indicated that the predicted heads are only moderately sensitive to changes in aquifer transmissivity, but are considerably more sensitive to changes in layer-to-layer leakance parameters (see Appendix C).

The flow model was then calibrated using data collected during aquifer performance testing in 1987. A transient mode simulation was constructed in which a single well was pumped at the constant rate of 515 GPM for a period of 72 hours. The initial condition hydraulic parameters for this calibration are shown in Table 7-1. For this calibration we used the data set collected from OBS-300 and OBS-600 during pump testing of R.O. Well 1 by Missimer & Associates, Inc., in June of 1987. The five layer model was used for these calibration runs, and transmissivity, leakance, and storativity were each interactively modified until a close match between predicted and observed head changes was obtained.

The FTWORK model requires stipulation of specific storage instead of storativity. The measured values of storativity in the Yorktown Aquifer averaged 4.1×10^{-4}. Dividing this value by the aquifer thickness of 130 feet resulted in a specific storage of 3.15×10^{-6} ft^{-1}. Transient calibration determined that a specific storage of 3.2×10^{-6} ft^{-1} provided the best fit, which agrees very closely to the original number.

After this initial calibration process, the difference between computed summer and winter heads matched the observed differences very well. The results of these two steady-state runs are shown in Table 7-2. Excluding the head differences in MW-

TABLE 7-2. Steady state drawdowns and summer/winter head differences calculated by the model after *hydraulics* calibration.

OBSERVATION WELL	COMPUTED[A] SUMMER DRAWDOWN	COMPUTED[B] WINTER DRAWDOWN	COMPUTED SUMMER/ WINTER HEAD DIFFERENCE	OBSERVED SUMMER/ WINTER HEAD DIFFERENCE	RESIDUAL BETWEEN COMPUTED/ OBSERVED DIFFERENCES
OCEAN	7.55	3.49	4.06	3.82	0.24
OBS-300	12.70	5.24	7.46	7.81	-0.35
OBS-600	12.35	5.01	7.34	8.12	-0.78
MW-510	10.60	4.55	6.05	5.94	0.11
MW-610	8.60	3.76	4.84	7.31[C]	-2.47[C]

Notes: All values reported in feet. Excluding the anomalous value for MW-610, the average residual between the computed and observed seasonal head differences is 0.20 feet.

[A] Summer drawdowns based on four measurements made in August, 1990, with an average pumping rate of 3.55 MGD

[B] Winter drawdowns based on four measurements made in February, 1991, with an average pumping rate of 1.55 MGD

[C] Anomalous observed head difference in MW-610.

610 because of an observed head anomaly, the residual between the average computed and average observed summer/winter head difference less than 0.20 feet.

Solute Transport Calibration

Much more involved than hydraulic calibration was the process of solute transport calibration. In addition, the data set relating to water quality was much more detailed and is not affected factors such as well efficiency. The total dissolved concentration data indicate The transport model utilizes more variables than the hydraulic model alone, and interactions among the variables are complex. The transport model proved to be considerably more sensitive to changes in inter-layer leakance values than the flow model. If the initial hydraulic calibration process is thought of as coarse-tuning, then the transport calibration process is similar to a fine-tuning of the numerical representation of the aquifer system.

The two-year average TDS increase rate measured in the supply wells is 1.38 mg/l per day. This rate was used as the calibration target. Seasonal variations in wellfield pumpage cancel each other out with regards to solute movement, so only the average wellfield pumpage of 2.36 million gallons per day (MGD) was used during the calibration runs. The model was run hydraulically in steady state mode, using 500 to 700 flow iterations to lower the budget error to less than 0.01 percent.

Initial transient transport model runs resulted in TDS rates-of-change that were much lower than those observed during the first two years of pumpage. Porosity and dispersivity changes alone were insufficient to adequately calibrate the model. Therefore, adjustments were made to the flow field hydraulics in order to properly simulate the observed TDS changes. Effective porosity values and the vertical hydraulic conductivity of the mid-Yorktown aquitard were the most sensitive parameters. Aquitard leakance was adjusted upward, and production zone transmissivity adjusted downward until the simulated TDS rate-of-change was very close to the observed rate of 1.38 mg/l per day. Each modification of the transport model hydraulic parameters required a new set of hydraulic calibration runs in both transient and steady state modes to assure that the resulting head distributions remained very close to observed values. This process was repeated 14 times, involving over 100 model runs, and over one million model iterations.

When the computed TDS rate-of-change was close the observed rate-of-change, and the water levels were still very close to the observed values (Table 7-3), the model was said to be calibrated and validated. The final model runs indicated a TDS concentration rate-of-change of 1.40 mg/l/day, which is very close to the 1.38 mg/l/day observed at the wellfield during the first two years of water quality records. Two final steady-state flow models were run using the U.S. Geological Survey MODFLOW code to generate a new set of summer/winter head differences. The results of these runs indicate that the model computed summer/winter head differences are within 0.48 feet of the observed head differences (Table 7-3).

Hydraulic coefficients for the calibrated model were determined through the use of a simulated three day pump test. Results from this pump test simulation are shown in Figures 7-1 and 7-2. The calibrated hydraulic coefficients for the mid-Yorktown Aquifer based on a leaky confined aquifer type curve match are given in Table 7-4. The hydraulic coefficients for each layer before and after the calibration process are shown in Table 7-5. These values are favorably comparable to the values determined by the actual aquifer tests (Missimer and Associates, Inc. 1987).

A sensitivity analysis was performed using the steady state hydraulic model to determine the sensitivity of the relationship between changes in leakance parameters and the leakage across the mid-Yorktown aquitard. This analysis indicated that the solute transport model is not sensitive to small changes in transmissivity. The leakage of water from the aquitard and the underlying lower Yorktown aquifer into the production zone has an approximately linear, one-to-one relationship with the leakance term between layers 2 and 3. Therefore, the rates of TDS change

TABLE 7-3. Steady state drawdowns and summer/winter head differences calculated by the model after *solute transport* calibration.

OBSERVATION WELL	COMPUTED[A] SUMMER DRAWDOWN	COMPUTED[B] WINTER DRAWDOWN	COMPUTED SUMMER/ WINTER HEAD DIFFERENCE	OBSERVED SUMMER/ WINTER HEAD DIFFERENCE	RESIDUAL BETWEEN COMPUTED/ OBSERVED DIFFERENCES
OCEAN	7.04	3.26	3.78	3.81	-0.03
OBS-300	12.25	5.03	7.22	7.81	-0.59
OBS-600	11.86	4.78	7.08	8.12	-1.04
MW-510	9.93	4.24	5.69	5.94	-0.25
MW-610	8.27	3.60	4.67	7.31[C]	-2.64[C]

Notes: All values reported in feet. Excluding the anomalous value for MW-610, the average residual between the computed and observed seasonal head differences is 0.48 feet.

[A] Summer drawdowns based on four measurements made in August, 1990, with an average pumping rate of 3.55 MGD

[B] Winter drawdowns based on four measurements made in February, 1991, with an average pumping rate of 1.55 MGD

[C] Anomalous observed head difference in MW-610

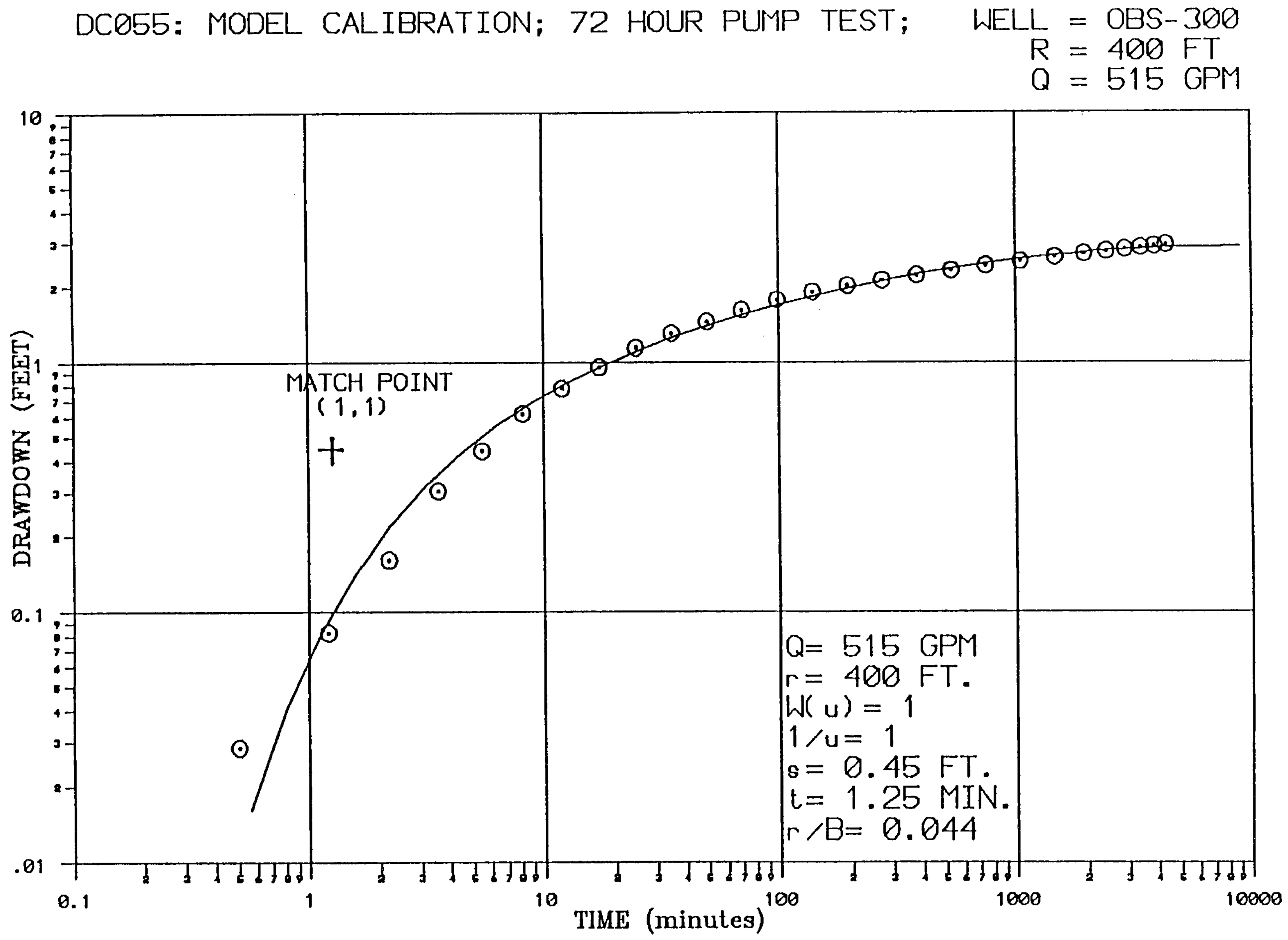

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FIGURE 7-1. TIME-DRAWDOWN DIAGRAM FOR OBS-300 RESULTING FROM A SIMULATION OF A THREE DAY TRANSIENT PUMPTEST OF R.O. WELL 1 AT A RATE OF 515 GALLONS PER MINUTE.

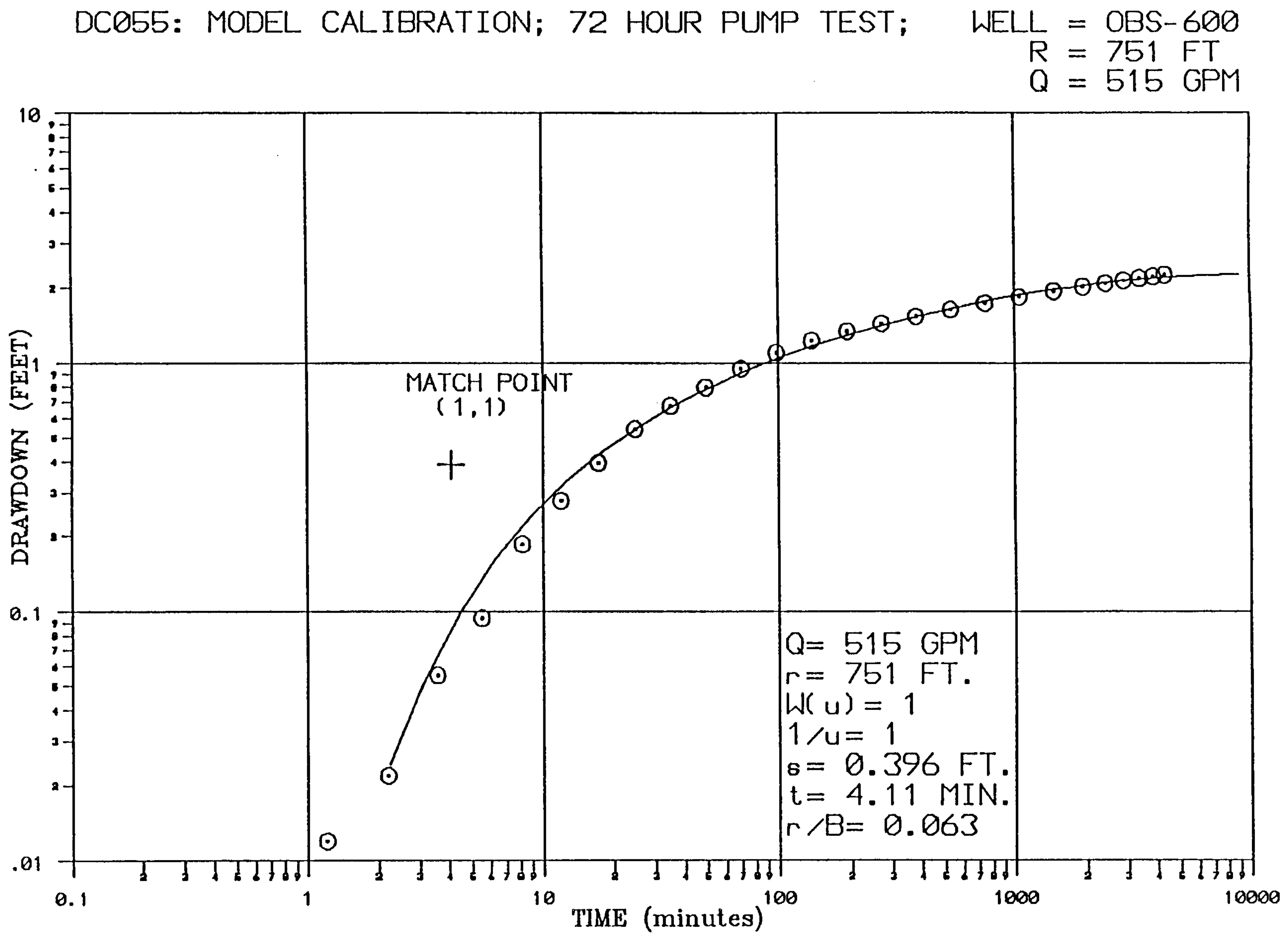

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FIGURE 7-2. TIME-DRAWDOWN DIAGRAM FOR OBS-600 RESULTING FROM A SIMULATION OF A THREE DAY TRANSIENT PUMPTEST OF R.O. WELL 1 AT A RATE OF 515 GALLONS PER MINUTE.

TABLE 7-4. Mid-Yorktown Aquifer coefficients determined by the Hantush-Jacob method (1955) from a simulated three day transient pumptest using the calibrated model.

OBSERVATION WELL	TRANSMISSIVITY (gpd/ft)	STORATIVITY $((ft^3/ft^2)/ft)$	LEAKANCE (gpd/ft^3)
OBS300	131000	3.81×10^{-4}	1.8×10^{-3}
OBS600	149000	4.02×10^{-4}	1.04×10^{-3}

NOTES: The curve-matching derived values are different from those used to specify the model layers because of the interaction between leakage and transmissivity in a multilayer system. See Figures 7-1 and 7-2 for data and best fit curves.

TABLE 7-5. Hydraulic coefficients before and after model calibration

MODEL LAYER	TOTAL DISSOLVED SOLIDS CONCENTRATION (mg/l)	BEFORE CALIBRATION				AFTER FLOW AND TRANSPORT CALIBRATION			
		THICKNESS (feet)	K_h [A] (gpd/ft^2)	K_v (gpd/ft^2)	K_v/K_h RATIO	THICKNESS (feet)	K_h (gpd/ft^2)	K_v (gpd/ft^2)	K_v/K_h RATIO
1	1000	100	965	193	5	40	769	23.1	33
2	2400	40	965	193	5	90	769	23.1	33
3	6200	50	145	9.65	15	60	154	1.12	137
4	7900	30	823	145	5.7	30	769	23.1	33
5	13,500	180	289	19.3	5	130	577	9.65	60

Notes:

K = hydraulic conductivity
K_h = horizontal hydraulic conductivity
K_v = vertical hydraulic conductivity

[A] Initial hydraulic conductivity determinations were based on a value derived from the transmissivity at R.O. Well 1 (T = 135,100 gpd/ft; average of aquifer tests), and the thickness of the mid-Yorktown Aquifer (140 ft). K = (135,100 gpd/ft)/(130 ft) = 1231 gpd/ft^2.

predicted by the solute transport model are sensitive to the leakance parameter, or the vertical hydraulic conductivity of the aquitard (model layer 3). However, the model was calibrated using high quality hydraulic response and water quality history data, hence the model predictions of near-term water quality changes are considered to be very reliable.

Predictive Scenarios

After model calibration, a long term model was run to simulate the Baum Tract wellfield pumping at its current annual average rate of 2.36 MGD. Time steps of 0.1 to 0.4 day duration were used for a series of model runs which totaled 3,800 days, starting August 1, 1989. TDS concentrations were calculated through time using the calibrated model. The results of this long term simulation are shown in Figure 7-3. On this figure is also shown the actual average water quality derived from over 800 samples collected in all eight supply wells. Although the lines do not exactly overlap, the critical comparison is that they have the same slope, indicating the same rate of high TDS water influx, or upconing. The change in concentration as a function of time, plotted against time, is shown in Figure 7-4. This shows that the rate of TDS influx on a day-by-day basis, and is simply the slope (first derivative) of the concentration versus time curve. The model shows a rapid rise in TDS concentrations immediately after the wellfield is turned on. This finding is in agreement with the observed TDS concentrations in the pumped wells. The rate of change remains roughly constant for a few hundred days at a rate of about 1.4 mg/l per day. This was the calibration criterion. Following the 800 day period of record, the model predicts a gradual decline in the rate of TDS concentration increase. This rate declines along a linear path, and probably becomes asymptotic with a rate of 0 mg/l per day as time goes on. The result of this is that the TDS concentration curve rises at a steadily decreasing rate, ultimately reaching a steady state value after some time in excess of 15 or 20 years. It is important to emphasize that this model is based on two years of water quality only, and very long term predictions must necessarily be qualified as projections based on our best understanding of the

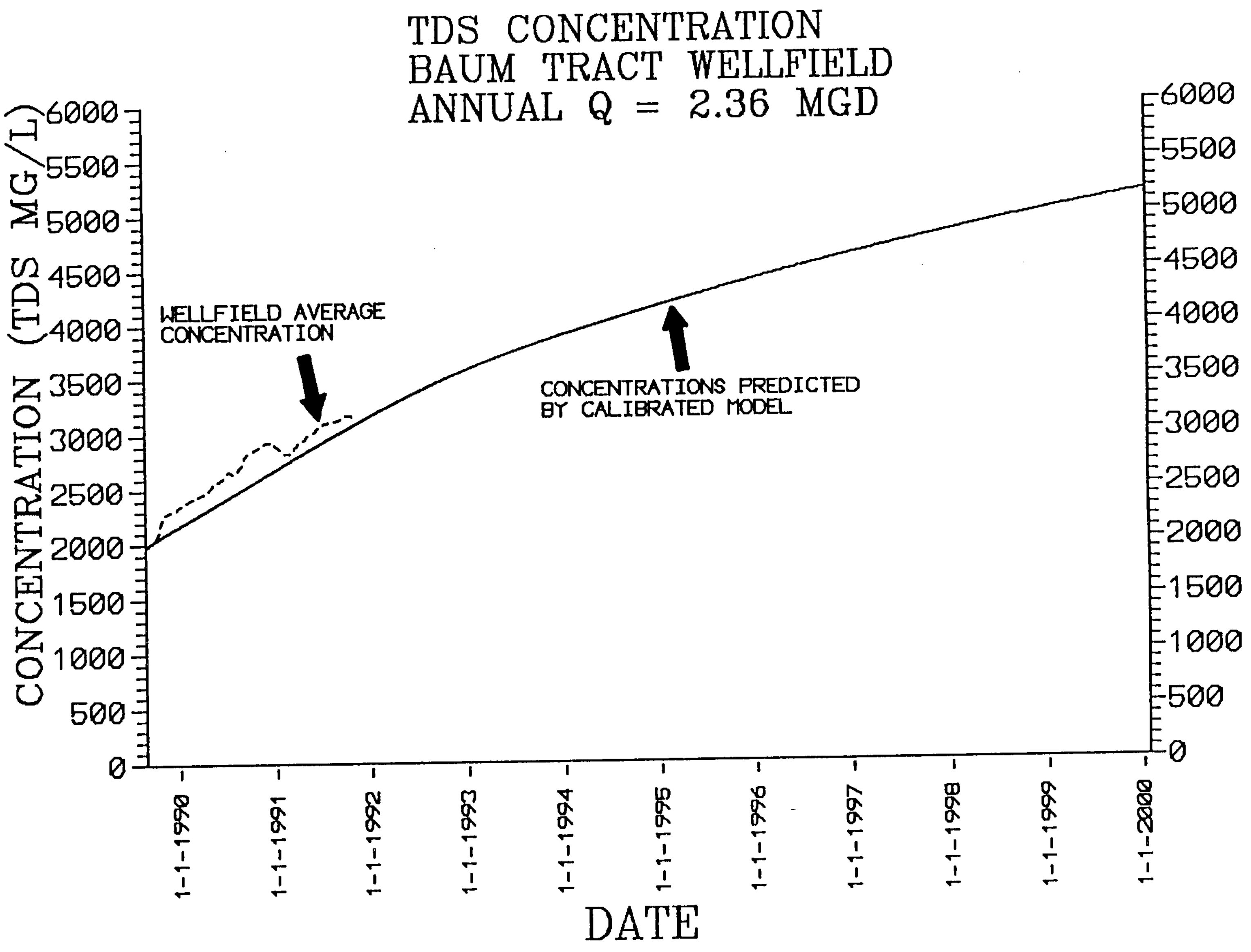

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FIGURE 7-3. MODEL PREDICTED CHANGES IN AVERAGE WELLFIELD TOTAL DISSOLVED SOLIDS CONCENTRATION AT THE CURRENT AVERAGE ANNUAL WELLFIELD PUMPING RATE OF 2.36 MILLION GALLONS PER DAY.

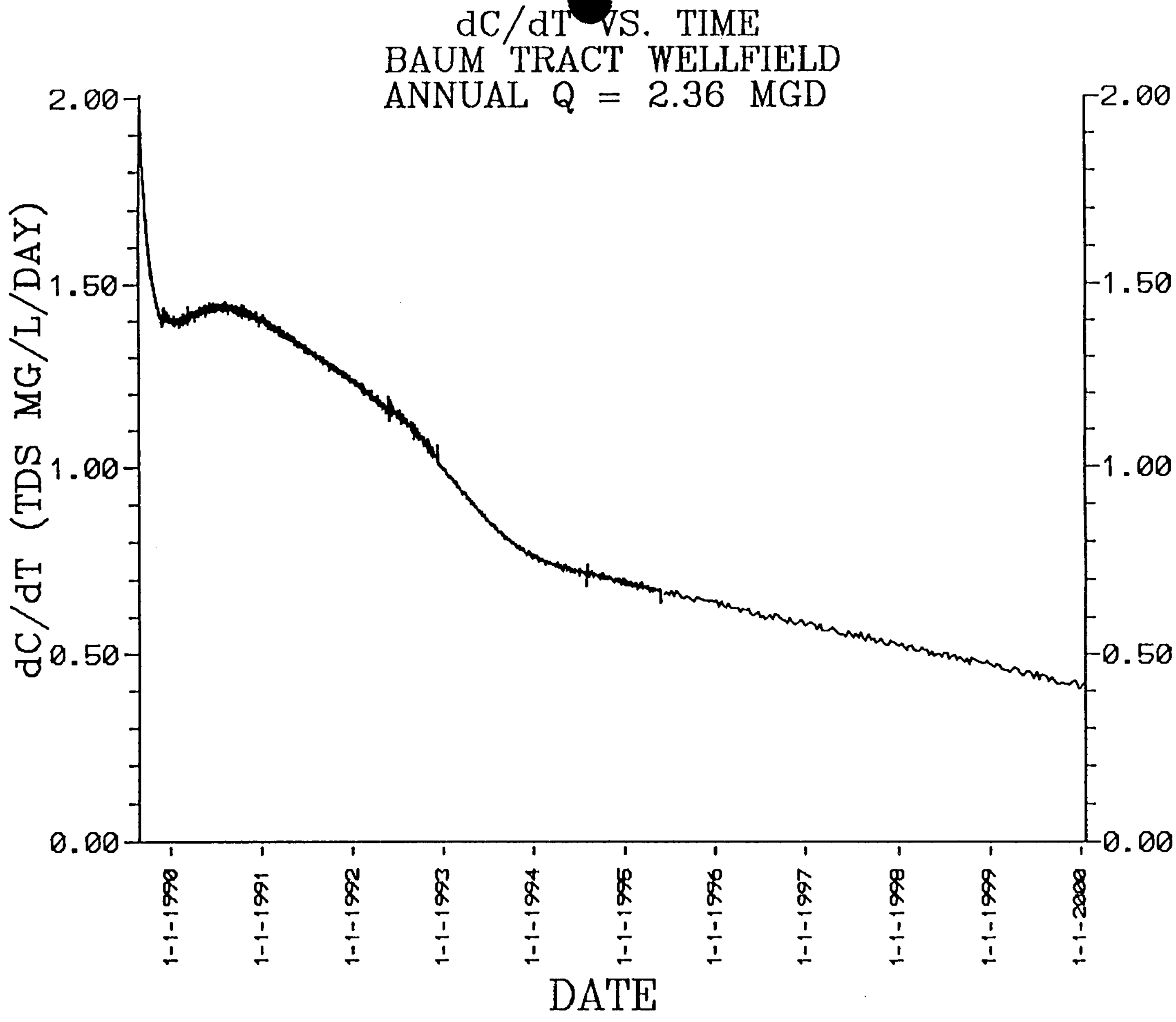

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FIGURE 7-4. MODEL PREDICTED CHANGES IN WELLFIELD TOTAL DISSOLVED SOLIDS CONCENTRATION RATE-OF-CHANGE-PER-DAY, THROUGH TIME, AT THE CURRENT AVERAGE ANNUAL WELLFIELD PUMPING RATE OF 2.36 MILLION GALLONS PER DAY.

hydrologic system.

A second scenario was constructed in which two wells spaced 1500 feet apart were pumped at an average rate of 0.86 MGD for 10 years. Plots of the TDS concentration versus time and the rate of TDS concentration change through time are shown in Figures 7-5 and 7-6. The slope of the concentration increase is less here than in the Baum Tract wellfield simulation. This is largely due to the increased spacing between the wells. In this scenario, however, the two wells are pumped harder than any of the wells in the previous scenario. The 0.86 MGD withdrawal rate used for these two wells results in a 300 GPM average daily pumping rate from each of these wells, as opposed to 205 GPM from each of the eight wells in the first scenario. This increased average withdrawal rate partially offsets the wider separation, so that TDS increases at approximately 0.8 mg/l per day after the initial period of stabilization. This rate of increase steadily declines, however, and after ten years it drops to 0.3 mg/l per day.

An additional scenario was run in which the Baum Tract wellfield withdrawal rate was reduced at the end of 1992, from an average 2.36 MGD to 1.5 MGD. The remaining 0.86 MGD would be made up by two new wells 8000 feet south of the present wellfield. This simulation was run until the end of the year 2003.

Discussion of Results

The observed increase in TDS concentration from 1970 mg/l in August of 1989, to 3100 mg/l in October 1991, is accurately simulated by the calibrated flow model. This scenario was run until December, 1992. A shift in the pumpage distribution by the addition of two new wells was simulated for January 1, 1993. This shift lowered the average withdrawal from the primary wellfield, which lowers its rate of TDS increase. In addition, mixing of relatively fresh water from the new wells dilutes the Baum Tract wellfield water, resulting in a sudden drop in the combined TDS concentration from 3600 mg/l to 3000 mg/l. Mixing of the water from these two

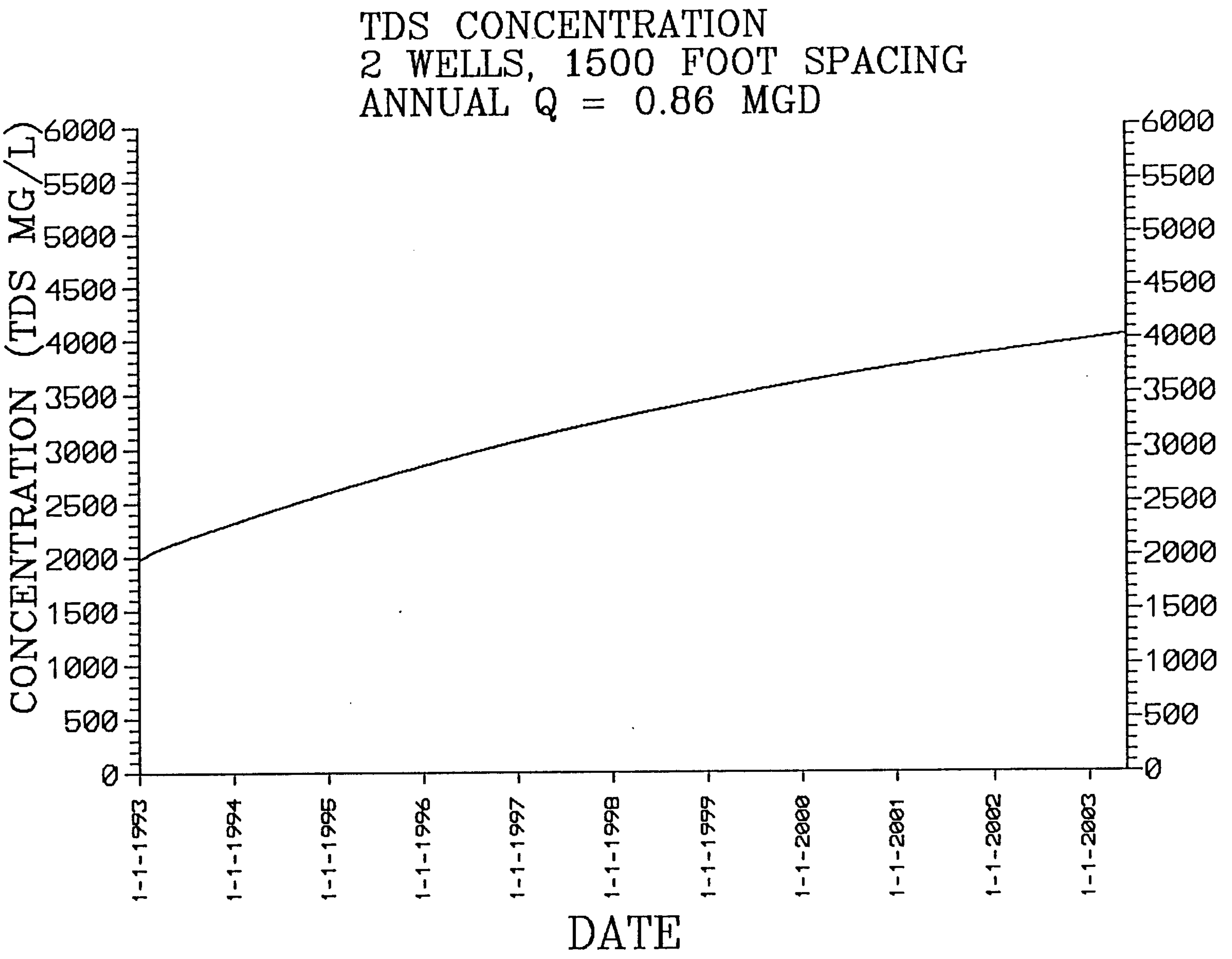

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FIGURE 7-5. MODEL PREDICTED CHANGES IN TOTAL DISSOLVED SOLIDS CONCENTRATION FOR TWO NEW WELLS PUMPING AT AN AVERAGE ANNUAL WELLFIELD PUMPING RATE OF 0.86 MILLION GALLONS PER DAY.

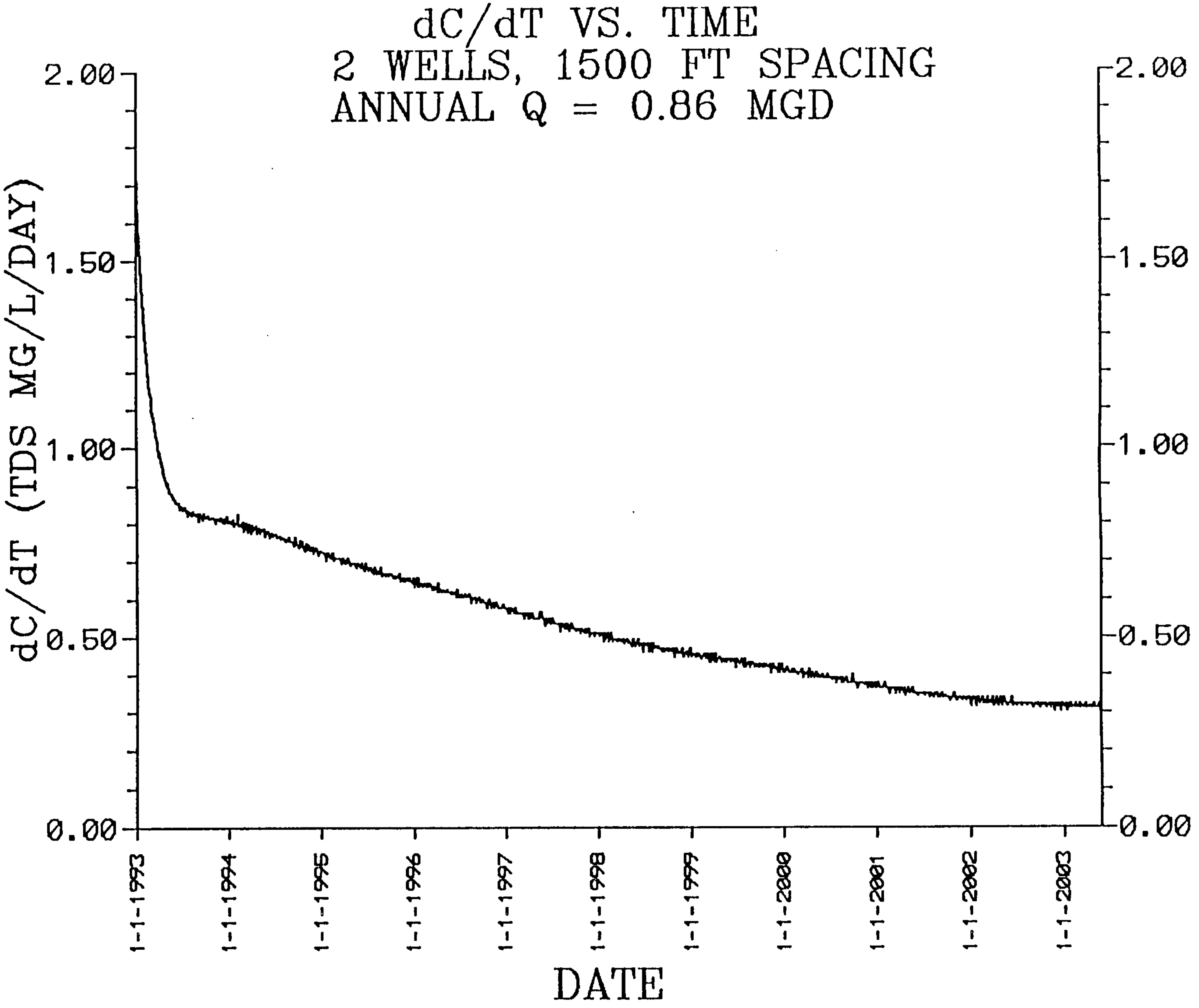

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FIGURE 7-6. MODEL PREDICTED CHANGES IN TOTAL DISSOLVED SOLIDS CONCENTRATION RATE-OF-CHANGE-PER-DAY, THROUGH TIME, FOR TWO NEW WELLS PUMPING AT AN AVERAGE RATE OF 0.86 MILLION GALLONS PER DAY.

sites results in a net feedwater quality that lies between the concentrations at the two wellfields. The predicted feedwater quality is shown in Figure 7-7, along with the projections from Scenario 1 and 2. The addition of the two wells provides an additional seven years to the water quality change curve. That is, instead of the feedwater quality reaching 4500 mg/l in 1996, the combined feedwater stream will not reach this concentration until approximately 2003.

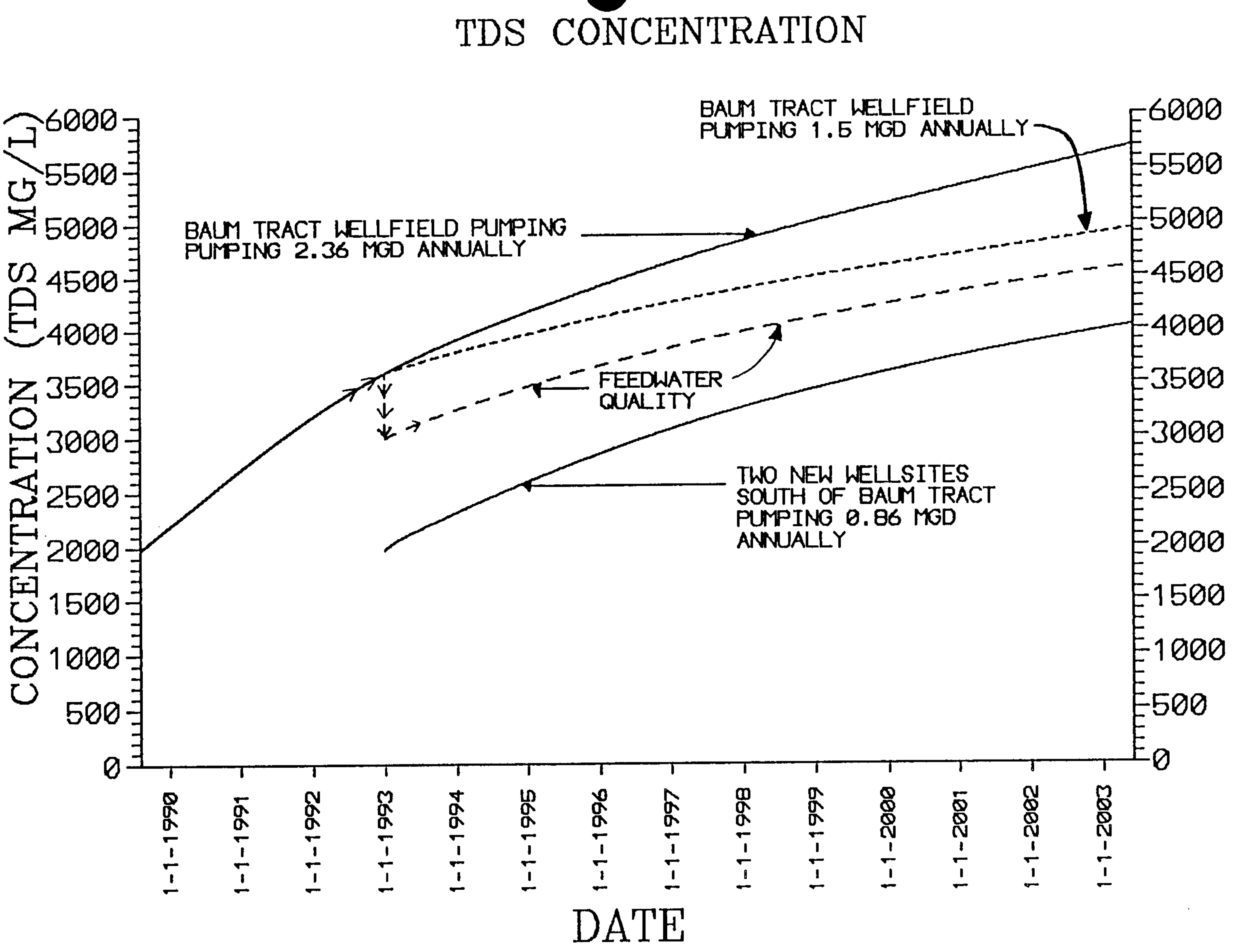

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FIGURE 7-7. MODEL PREDICTED TOTAL DISSOLVED SOLIDS CONCENTRATION FOR TWO WITHDRAWAL SCENARIOS: 1) PUMPING FROM THE BAUM TRACT WELLFIELD AT THE CURRENT ANNUAL AVERAGE WITHDRAWAL RATE OF 2.36 MGD UNTIL THE YEAR 2003; AND 2) PUMPING 2.36 MGD FROM THE BAUM TRACT WELLFIELD UNTIL 1/93, THEN DECREASING THE WITHDRAWAL TO 1.5 MGD UNTIL 2003, AND PUMPING 0.86 MGD FROM TWO NEW WELLS FROM 1/93 UNTIL THE YEAR 2003. FEEDWATER QUALITY FOR EACH WELLFIELD IS SHOWN IN ADDITION TO THE BLENDED FEEDWATER QUALITY.

VIII. WELLFIELD CONFIGURATION PLANNING

The high rate of TDS concentration change in the Baum Tract wellfield strongly suggests that all future wellfield expansion should use well spacings considerably greater than those used in the Baum Tract wellfield. The existing wellfield configuration at the Baum Tract is sufficiently dense that no further well installations in the Tract area should be considered. Analytical modeling of the Baum Tract wellfield was used to determined what linear spacing of wells would produce the same maximum drawdown in the wellfield center. This interactive modeling determined that the existing configuration is hydraulically equivalent to a linear configuration of eight wells with a well spacing of 600 feet.

Future wellfield expansion should proceed in such a manner that withdrawals cover the greatest area possible, reducing the maximum drawdown at new well sites relative to that which occurs at the Baum Tract. To achieve a minimum drawdown for a given wellfield withdrawal rate, the wellfield expansion should follow an approximately linear alignment parallel to the Atlantic Coast. The actual alignment used will be determined by well site availability and pipeline installation logistics. The well spacing should be as large as feasibly possible. A distance of approximately 1500 feet is recommended to reduce well interference effects and to spread the withdrawal load over a much greater area. Proposed supply and monitor well sites, and the suggested alignment for additional wellfield expansion, are shown in Figure 8-1.

The model developed during this investigation will provide an extremely valuable planning tool in proper water resource management for Dare County. The model can be updated and re-calibrated as new hydraulic and solute transport data become available, new wellfields can be simulated once test data are compiled, and economic forecasting can be aided by accurate projections of water supply infrastructure requirements.

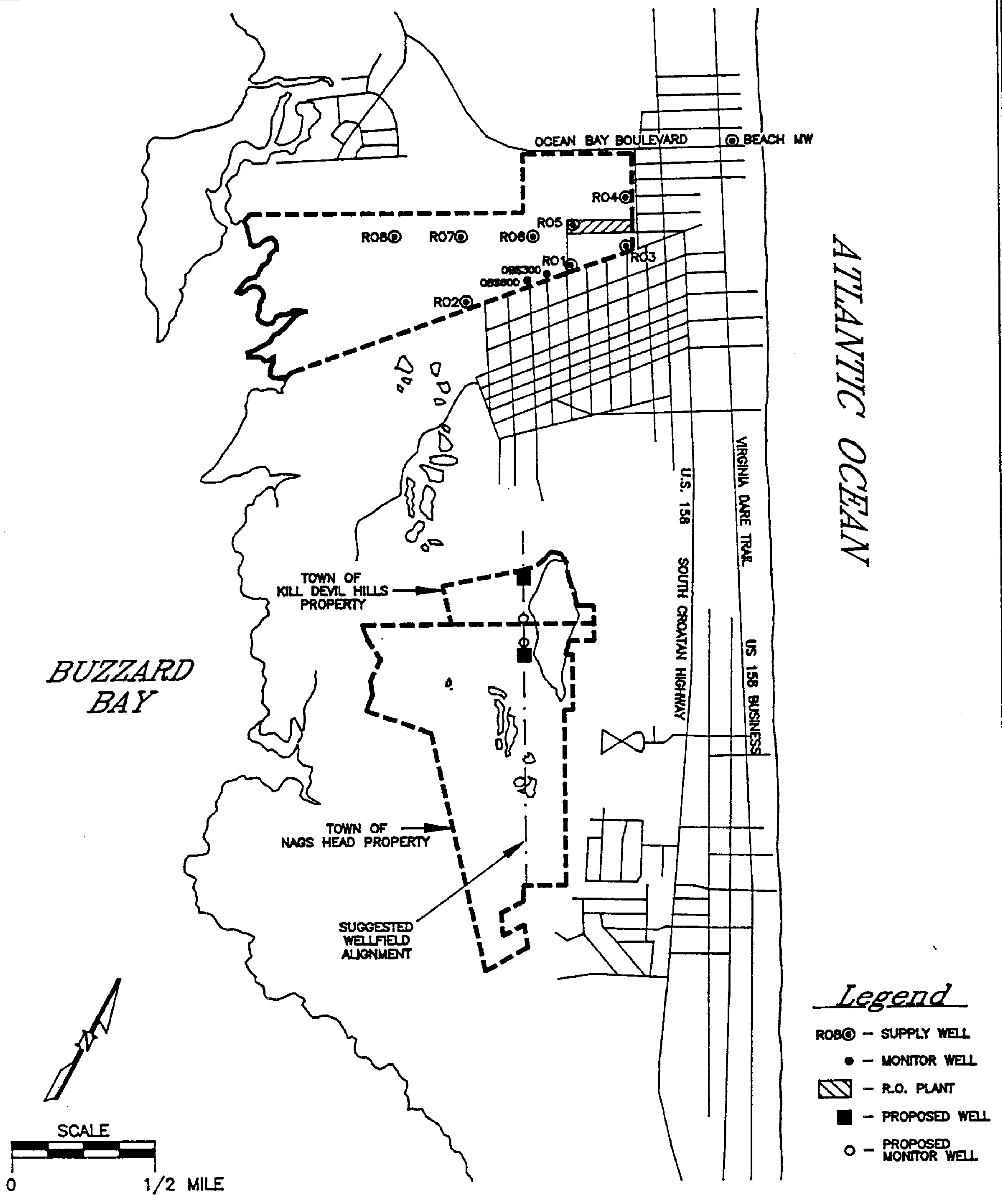

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FIGURE 8-1. MAP SHOWING EXISTING AND RECOMMENDED WELL LOCATIONS.

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X. GLOSSARY OF TERMS

aquifer	Rock or sediment in a formation, group of formations, or part of a formation which is saturated and sufficiently permeable to transmit economic quantities of water to wells or springs.
aquitard	A layer of low permeability that can store ground water and also transmit it slowly from one aquifer to another
aquifer performance test	A test made by pumping a well for a period of time and observing the change in hydraulic head in the aquifer. An aquifer test may be used to determine the capacity of the well and hydraulic characteristics of the aquifer.
boundary conditions	In numerical groundwater modeling, three types of boundary conditions are used: A) Type I, or Dirchlet boundaries, consist of prescribed or predefined water levels or heads and concentrations; B) Type II, or Neuman boundary conditions consist of prescribed flux conditions; these can be either positive, negative, or zero fluxes, of groundwater volume per unit time; and C) Type III, head dependent flux boundaries, in which the volume per unit time across the boundary is a function of the active cell head and the boundary conductance, area, and prescribed head.
BLS	Below land surface
below land surface	The depth below land surface to a specified point or horizon. This depth is a relative measure, and cannot be used for direct comparison with data from other sites.
cone of depression	A depression in the groundwater table or potentiometric surface that has the shape of an inverted cone and develops around a well from which water is being withdrawn. It defines the area of influence of a well. The shape of the depression is due to the fact that the water must flow through progressively smaller cross sections as it nears the well, and hence the hydraulic gradient becomes steeper near the well.
confined aquifer	An aquifer that is bound above and below by impermeable beds, or by beds of distinctly lower permeability than that of the aquifer itself.

confining bed	A body of material of low hydraulic conductivity that is stratigraphically adjacent to one or more aquifers. It may lie above or below the aquifer.
datum elevation	A permanently established horizontal plane, surface, or level to which soundings, ground elevations, water surface elevations, and tidal data are referred.
density stratification	The stratification of a body of water produced as a result of density differences in the water, the lightest layer occurring near the top and the heaviest layer at the bottom, usually caused by salinity differences.
drawdown	A lowering of the water table of an unconfined aquifer or the potentiometric surface of a confined aquifer caused by pumping groundwater from wells. Measured as the distance between the static water level and the surface of the cone of depression.
dynamic-equilibrium	A condition in which the amount of recharge to an aquifer system equals the amount of discharge from the system.
effective porosity	The ratio of the continuous void space (through which water can move) to the total volume of the material. Effective porosity is less than bulk porosity; it can be expressed as a percentage or as a decimal fraction.
feedwater	The supply of water used by a water treatment plant for processing into potable drinking water.
fully penetrating	A well drilled to the bottom of an aquifer, constructed in such a way that it withdraws water from the entire thickness of the aquifer.
groundwater model	A model of groundwater flow in which the aquifer is described by numerical equations with specified values for boundary conditions which are solved on a digital computer.
hydraulic conductivity	The volume of water that will pass through a unit area of material under a unit hydraulic gradient per unit of time. The commonly used units are gal/day/ft^2, or ft/day.
hydraulic gradient	The change in total head with a change in distance in a given direction. The direction is that which yields a maximum rate of decrease in head.
hydraulic parameters	Also referred to as aquifer parameters, the fundamental

	measures of flow in porous media: transmissivity, storativity, and leakance.
hydrogeology	The study of geology and hydrology as they relate to subsurface and surface waters.
leakage	The vertical movement of groundwater from one aquifer to another across a confining layer.
leakance	A measure of the ease with which groundwater can move vertically from one aquifer to another across a layer of lesser hydraulic conductivity, or a confining layer. It is equivalent to the vertical hydraulic conductivity divided by the confining layer thickness. Usually determined by means of controlled condition aquifer tests lasting three or more days.
lithology	The description of rocks, esp. in hand specimen and in outcrop, on the basis of such characteristics as color, mineralogic composition, and grain size; the physical character of a rock.
monitor well	A water well used for monitoring the water level and/or water quality of a specific zone of an aquifer. Usually of small diameter, four inches or less.
potentiometric surface	An imaginary surface representing the total head of groundwater in a confined aquifer that is defined by the level to which water will rise in a well.
production zone	The zone or vertical interval across which water is withdrawn from an aquifer.
radius of influence	The radial distance from the center of a well bore to the point where there is no lowering of the water table or potentiometric surface (the edge of its cone of depression).
reverse osmosis water treatment	The removal of salt and other chemicals from brackish or saline water by means of the reverse osmotic effect. Normal osmosis is the natural phenomenon which occurs when solutions with differing salt concentrations are separated by a semipermeable membrane. Water tends to pass through the membrane from the more dilute side to the more concentrated side, tending to equalize the concentrations on both sides of the membrane. In reverse osmosis water treatment, the process is reversed by applying a pressure to the brackish feedwater side of the membrane which is

	greater than the natural osmotic pressure. This causes nearly pure water to diffuse through the semipermeable membrane in the direction opposite to the normal osmotic flow.
salinity	The measure of the quantity of total dissolved solids in water.
solute	A chemical constituent which is dissolved in water (the solvent).
solute transport, advective	The process by which solutes are transported in groundwater by the bulk motion of the flowing groundwater.
solute transport, dispersive	The process by which solutes are transported in groundwater by diffusion and mixing due to microscopic variations in velocities within and between pores in the subsurface sediments.
specific capacity	An expression of the productivity of a well, obtained by dividing the rate of discharge of water from the well by the drawdown of the water level in the well.
static water level	The level of water in a well that is not being affected by withdrawal of groundwater.
storativity	The volume of water that a permeable unit will absorb or expel from storage per unit surface area per unit change in head. It is a dimensionless quantity. It is equal to the product of specific storage and aquifer thickness.
specific storage	The amount of water per unit volume of a saturated formation that is stored or expelled from storage due to compressibility of the mineral skeleton and the pore water.
TDS	Total dissolved solids
total dissolved solids	A term that expresses the quantity of dissolved material in a sample of water which is determined by the mass of the residue on evaporation, divided by the volume of water evaporated.
transmissivity	The rate of flow of water at a prevailing temperature, through a vertical strip of aquifer which is one unit wide and extends across the full saturated height of the aquifer, under a unit hydraulic gradient. Commonly expressed as gallons/day/ft,

	or ft^2/day.
upconing	The upward vertical movement of groundwater under a pumped well or wellfield from underlying aquifers into the pumped aquifer.
well casing	A metal, PVC, or fiberglass pipe, lowered into a bore hole during or after drilling and cemented into place. It prevents the sides of the bore hole from collapsing, prevents loss of drilling mud or other fluids into porous formations, and prevents unwanted fluids from entering the hole. A well may contain several strings of casing, the inner and smaller-diameter strings extending progressively deeper.
well efficiency	A measure of well performance, which depends on well design and construction factors; reported as the ratio of the observed specific capacity over the theoretical specific capacity; dimensionless.
well purging	The process of removing water from a water well prior to collecting water samples to assure that the water samples are representative of formation waters.
well screen	A filtering device, usually made of perforated or slotting well casing, used to keep unconsolidated sediment from entering the well.
well yield	The volume of water discharged from a well per unit time, either by pumping or by free flow.

Definitions taken from:

Bates, R.L., and Jackson, J.A., Eds., 1987, Glossary of Geology, 3rd Ed., American Geological Institute, Alexandria, Virginia, 788 p.

Driscoll, F.G., 1986, Groundwater and Wells, Johnson Division, St. Paul, Minnesota, 1089 p.

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APPENDIX A

SPECIFIC CAPACITY
AS A FUNCTION OF TIME
FOR R.O. SUPPLY WELLS 1 TO 8

SPECIFIC CAPACITY
AS A FUNCTION OF PUMPING RATE
FOR R.O. SUPPLY WELLS 1 TO 8

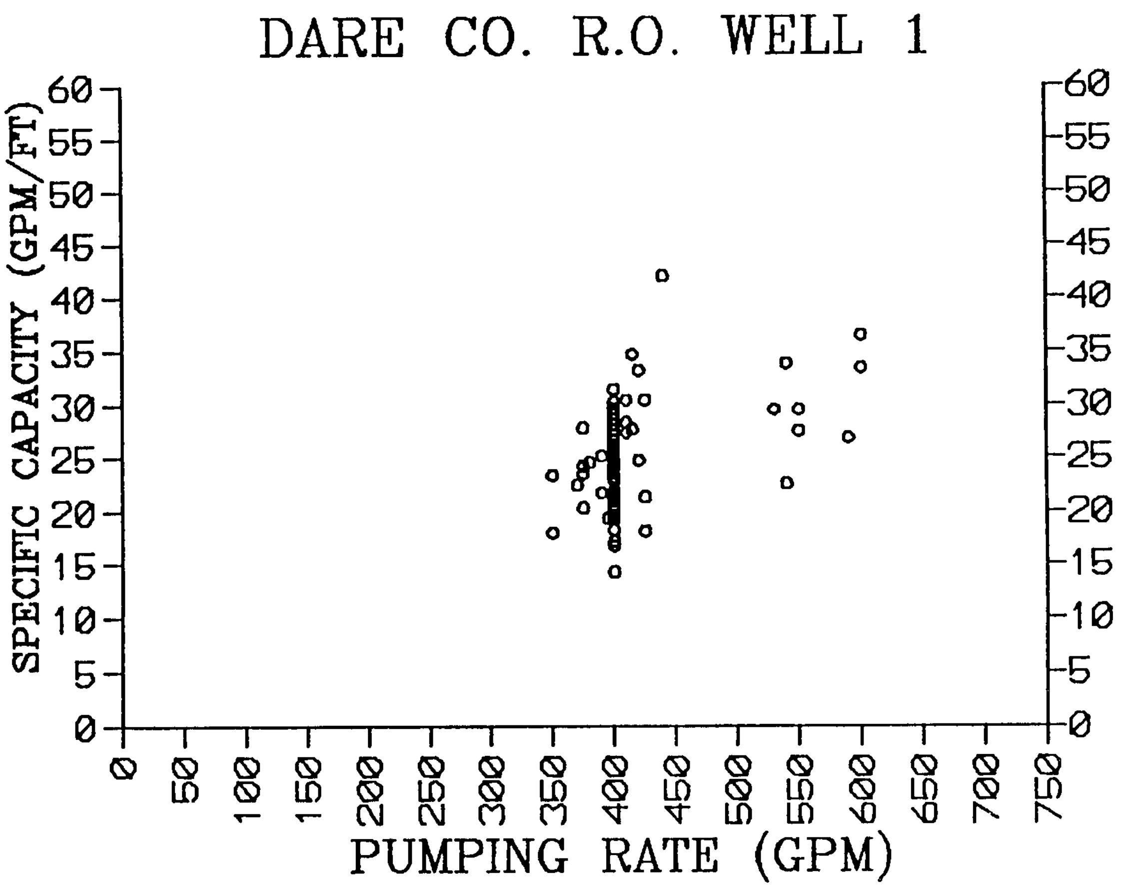

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FIGURE A-1. R.O. WELL 1 SPECIFIC CAPACITY VERSUS PUMPING RATE.

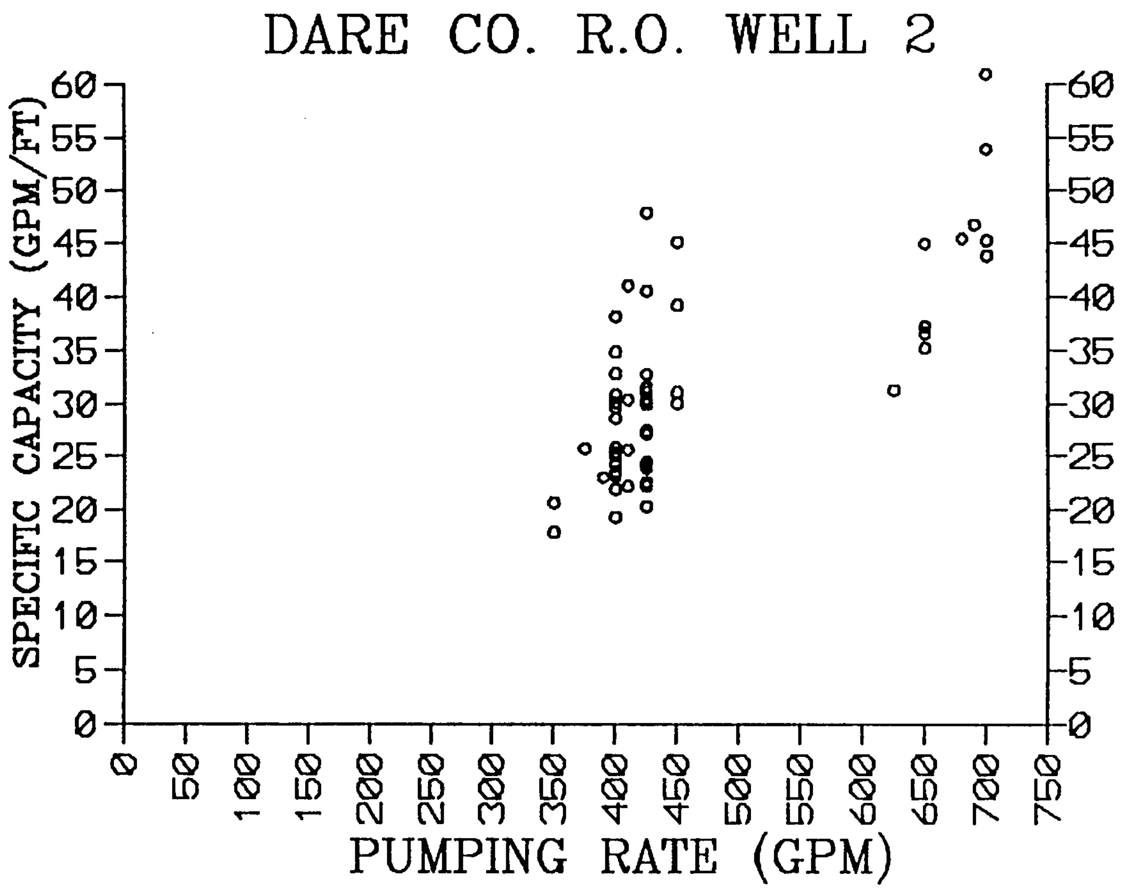

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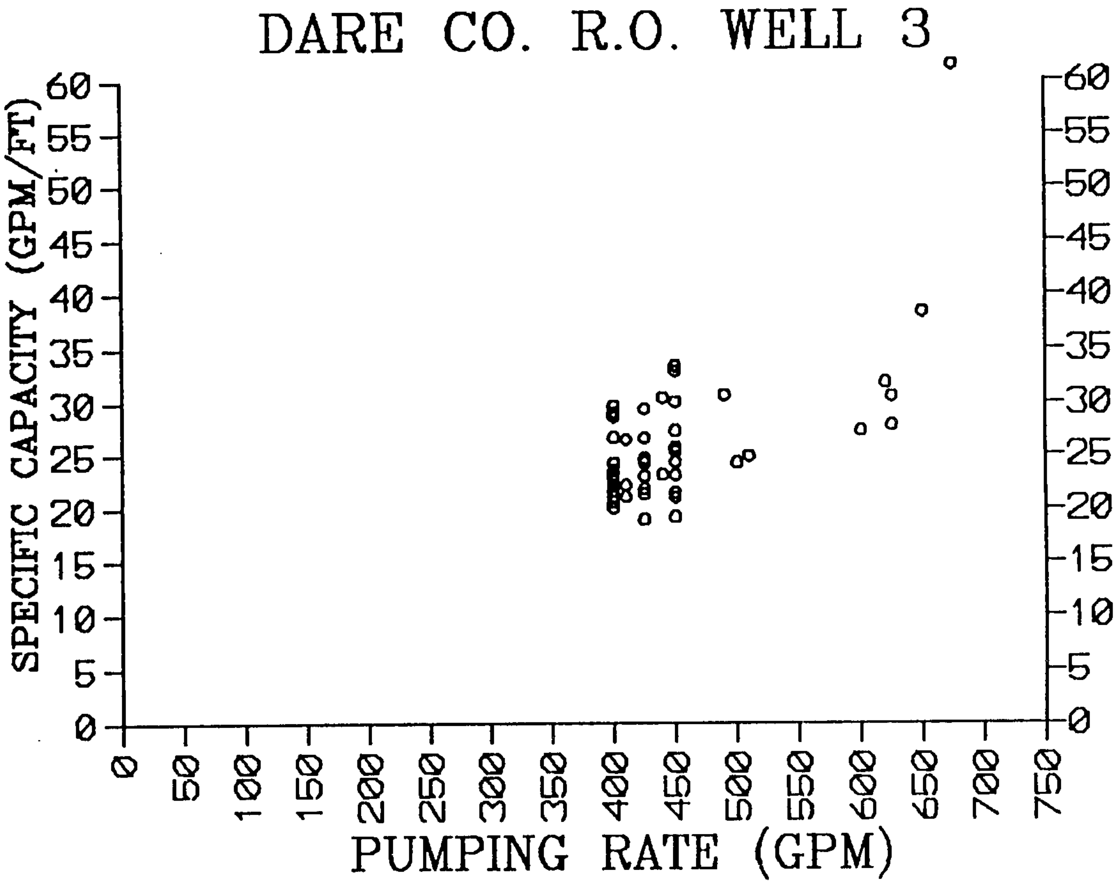
FIGURE A-2. R.O. WELL 2 SPECIFIC CAPACITY VERSUS PUMPING RATE.



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	PROJECT NAME: DARE COUNTY WELLFIELD	PROJECT NUMBER: CH0-401	

FIGURE A-3. R.O. WELL 3 SPECIFIC CAPACITY VERSUS PUMPING RATE.

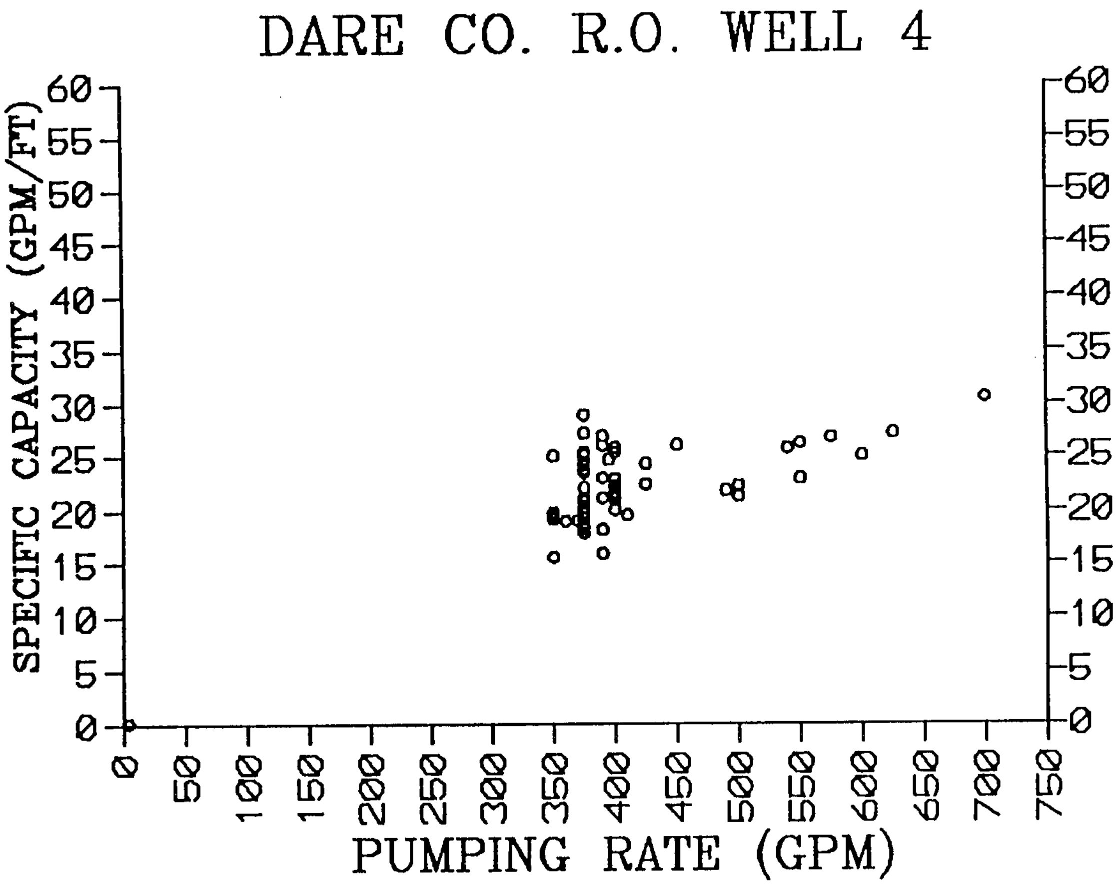

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FIGURE A-4. R.O. WELL 4 SPECIFIC CAPACITY VERSUS PUMPING RATE.

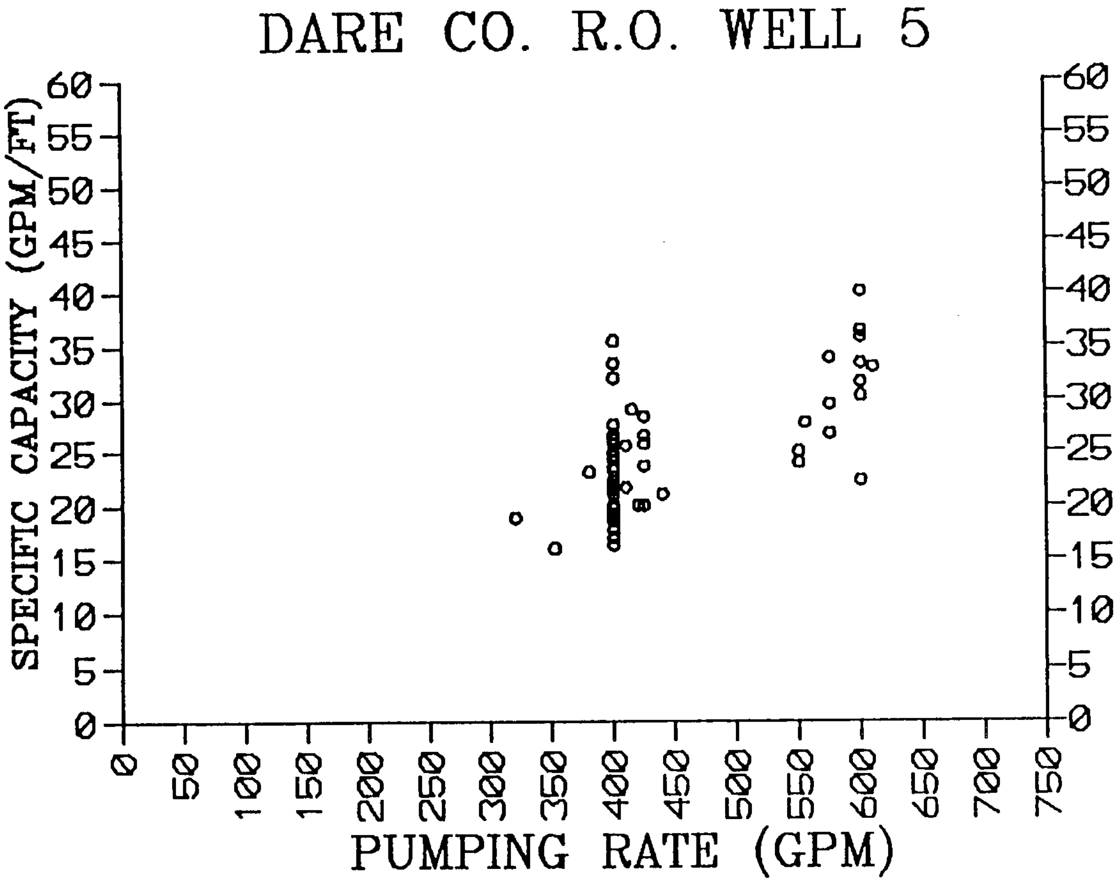

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FIGURE A-5. R.O. WELL 5 SPECIFIC CAPACITY VERSUS PUMPING RATE.

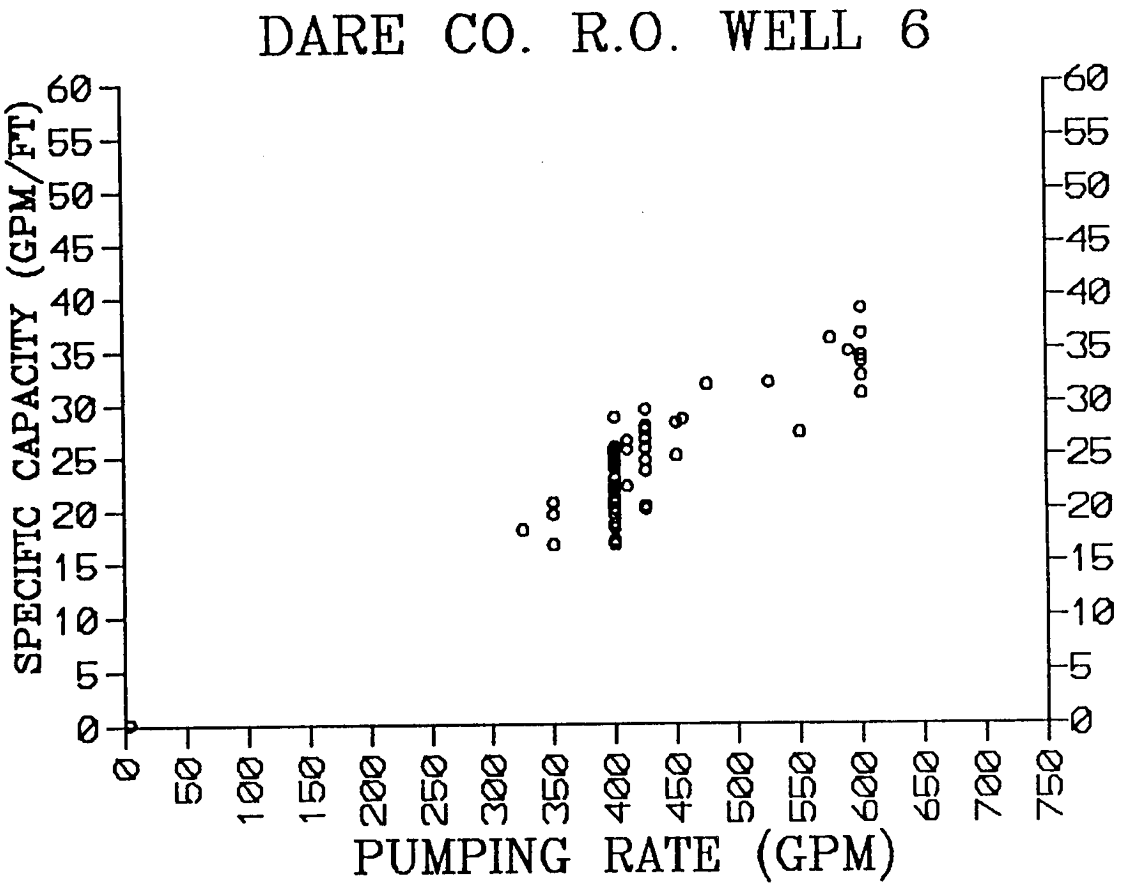

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FIGURE A-6. R.O. WELL 6 SPECIFIC CAPACITY VERSUS PUMPING RATE.

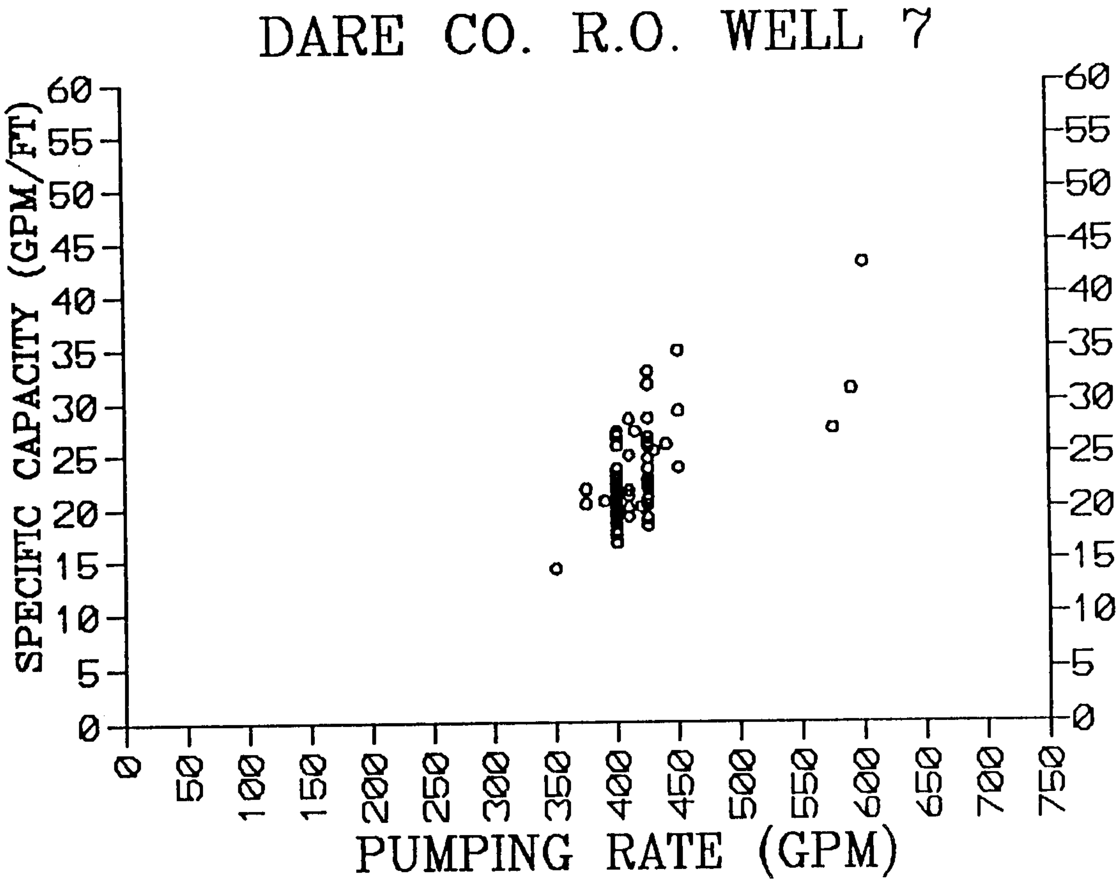

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FIGURE A-7. R.O. WELL 7 SPECIFIC CAPACITY VERSUS PUMPING RATE.

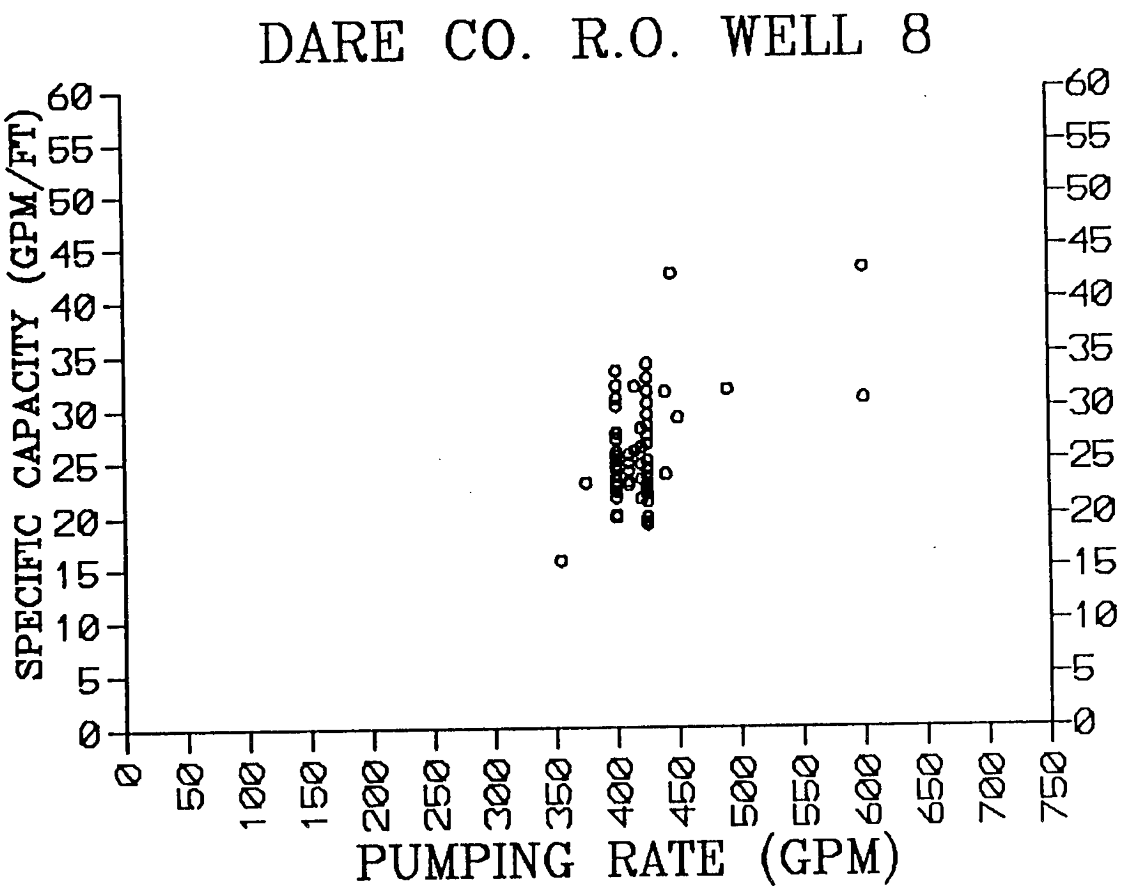

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FIGURE A-8. R.O. WELL 8 SPECIFIC CAPACITY VERSUS PUMPING RATE.

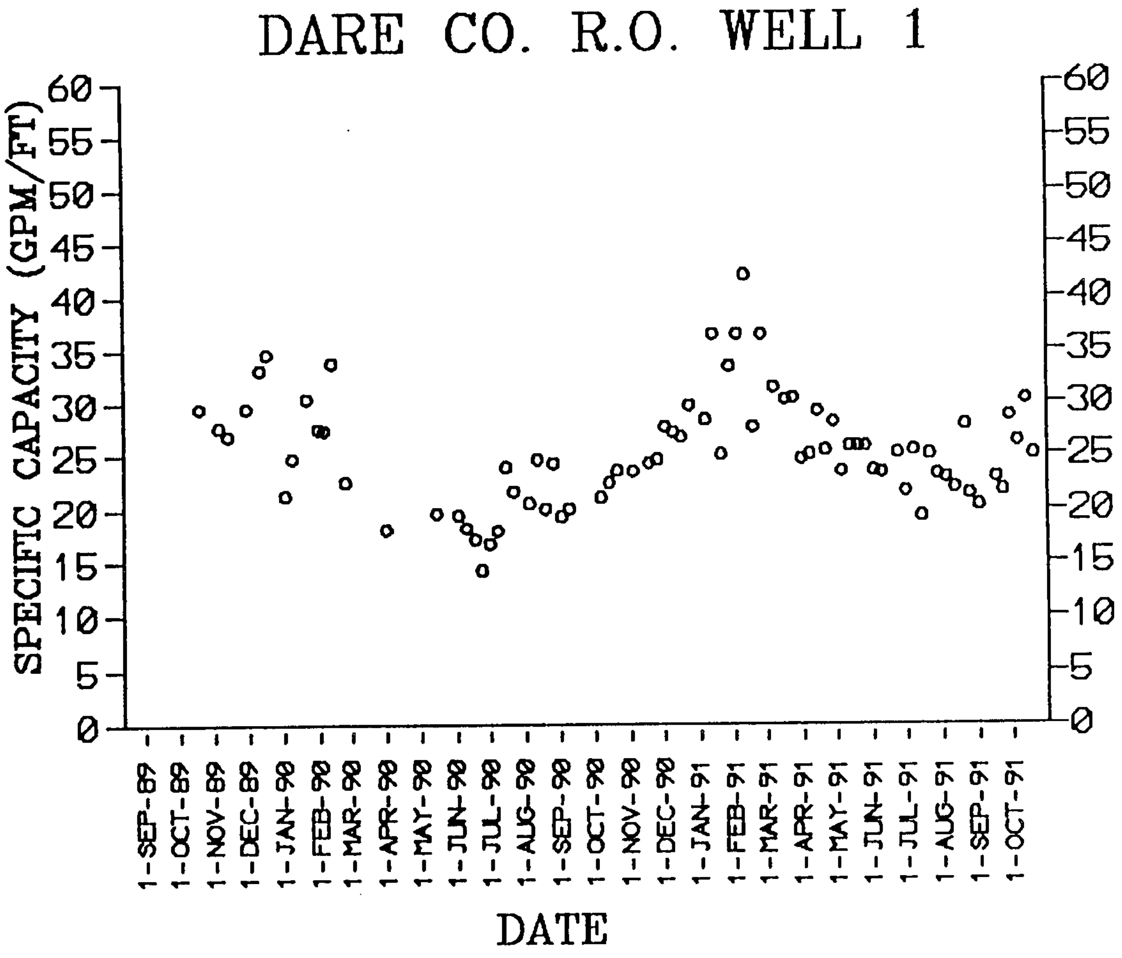

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FIGURE A-9. R.O. WELL 1 SPECIFIC CAPACITY VERSUS TIME.

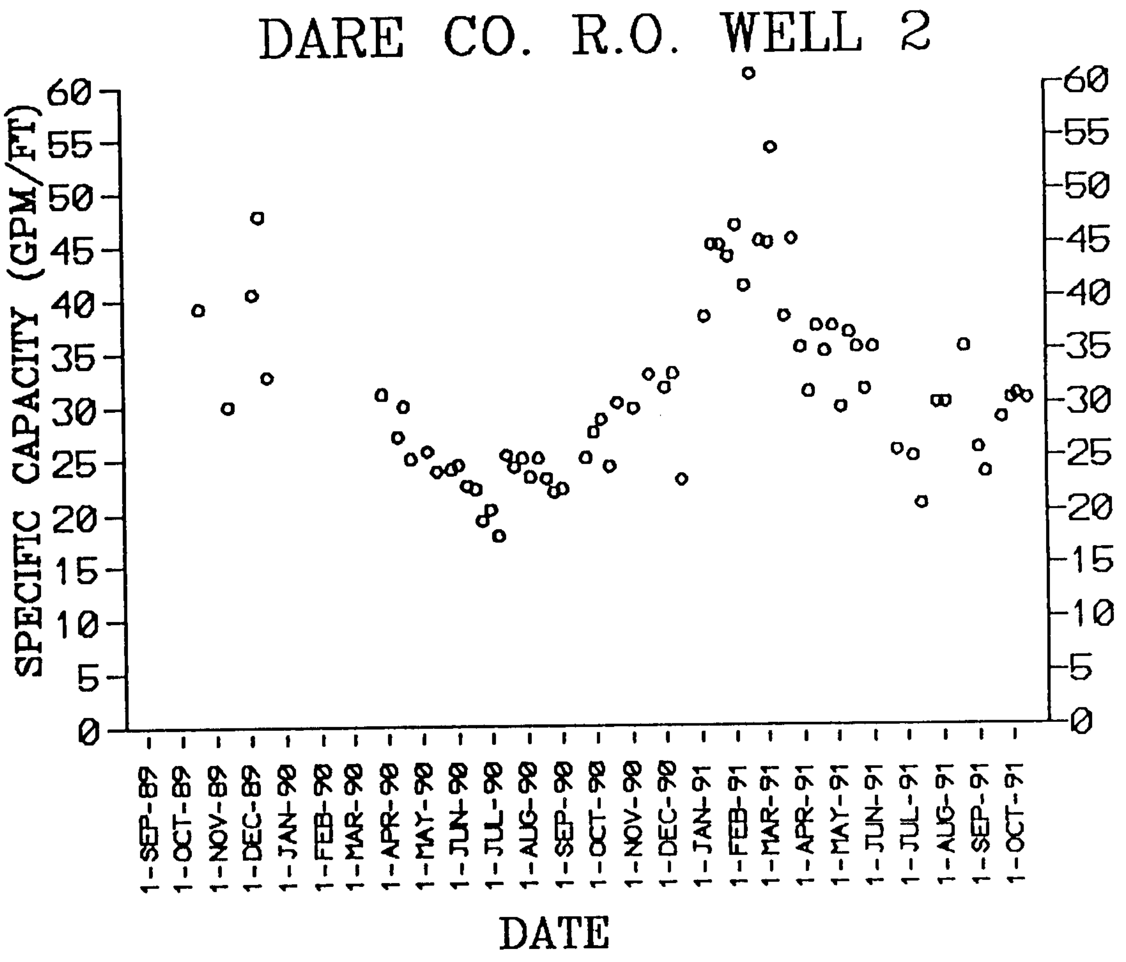

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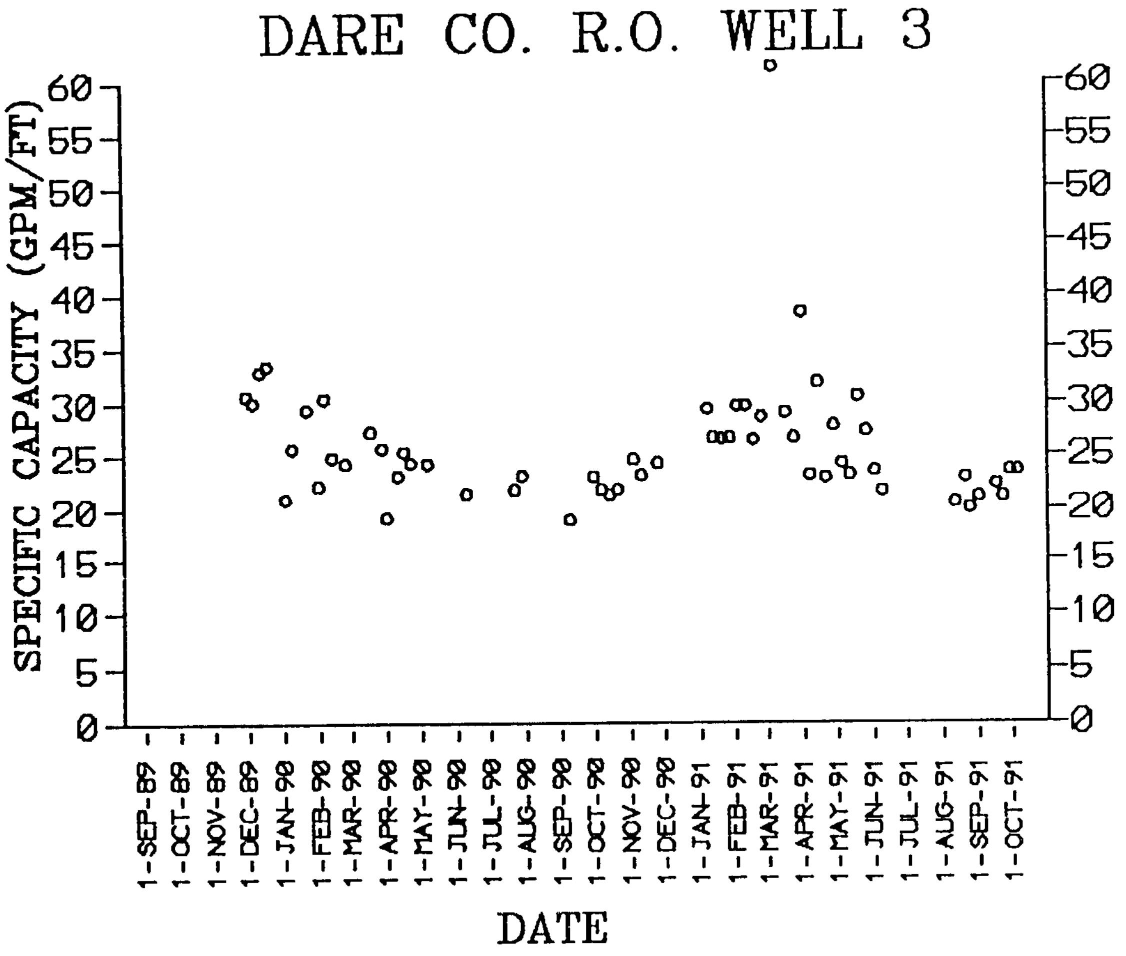
FIGURE A-10. R.O. WELL 2 SPECIFIC CAPACITY VERSUS TIME.



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	PROJECT NAME: DARE COUNTY WELLFIELD	PROJECT NUMBER: CHO-401	

FIGURE A-11. R.O. WELL 3 SPECIFIC CAPACITY VERSUS TIME.

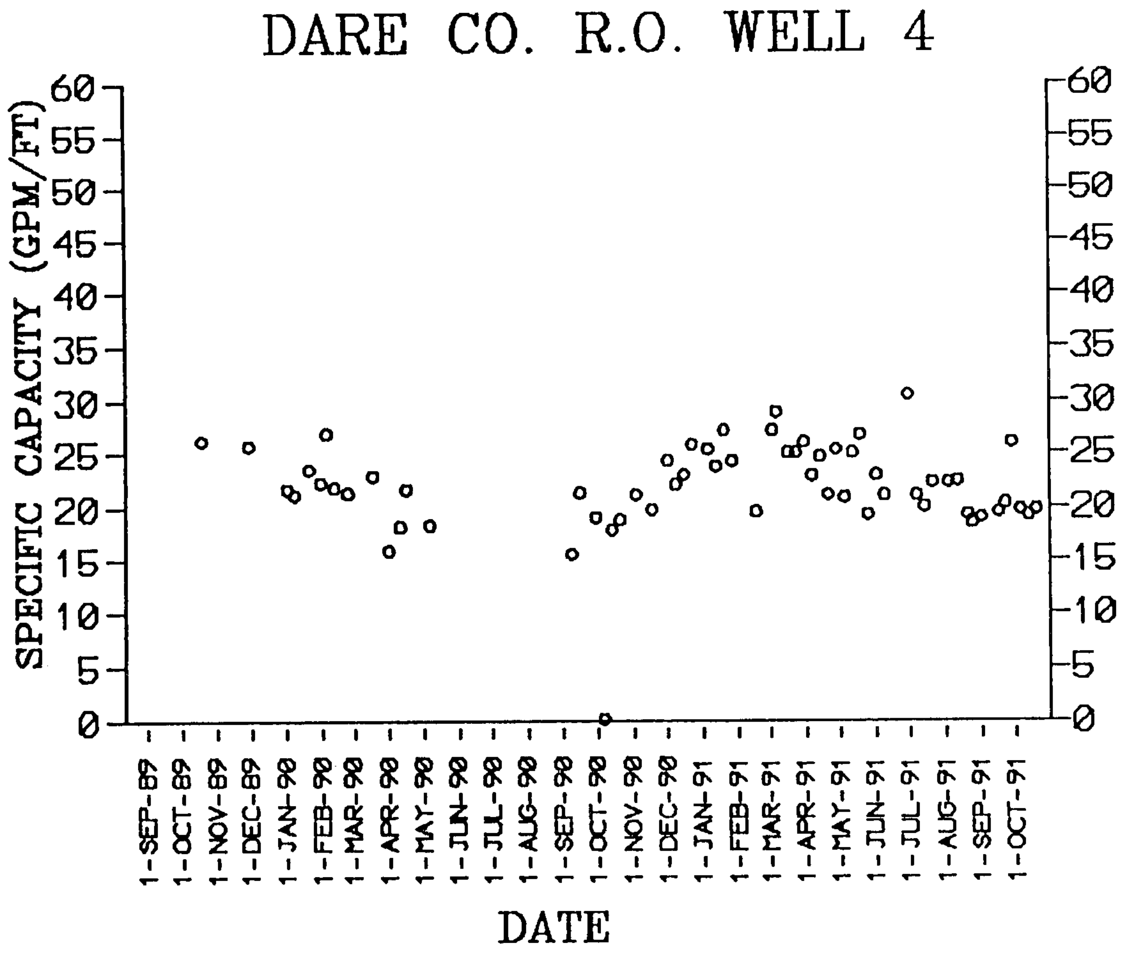

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FIGURE A-12. R.O. WELL 4 SPECIFIC CAPACITY VERSUS TIME.

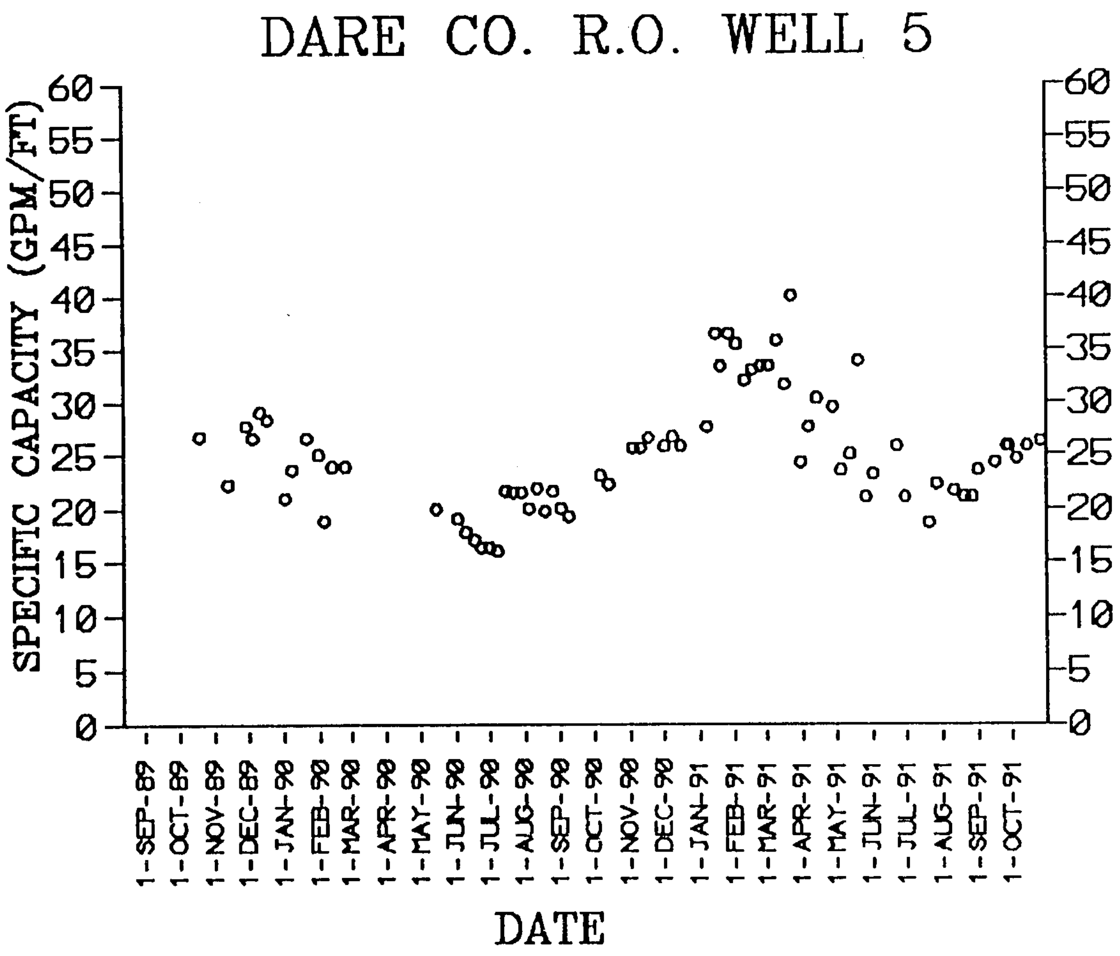

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FIGURE A-13. R.O. WELL 5 SPECIFIC CAPACITY VERSUS TIME.

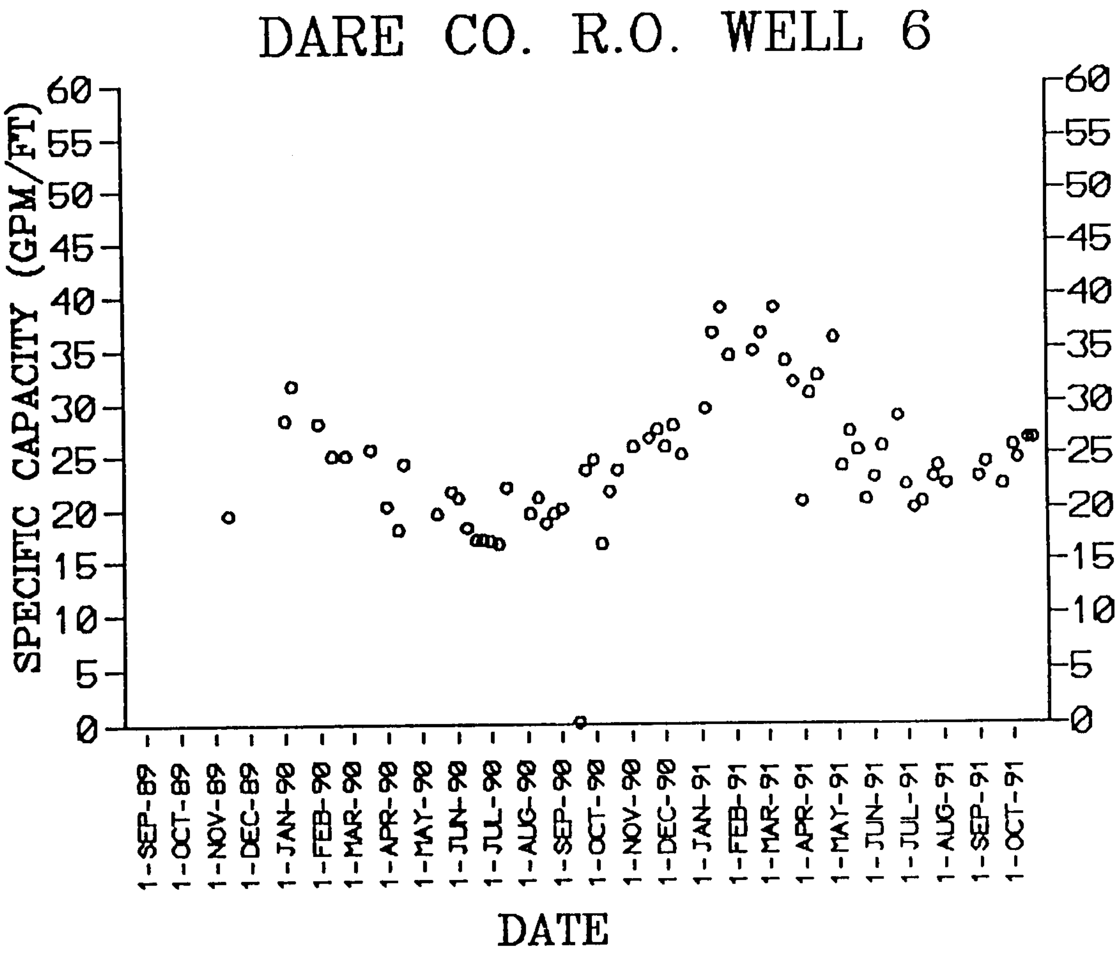

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FIGURE A-14. R.O. WELL 6 SPECIFIC CAPACITY VERSUS TIME.

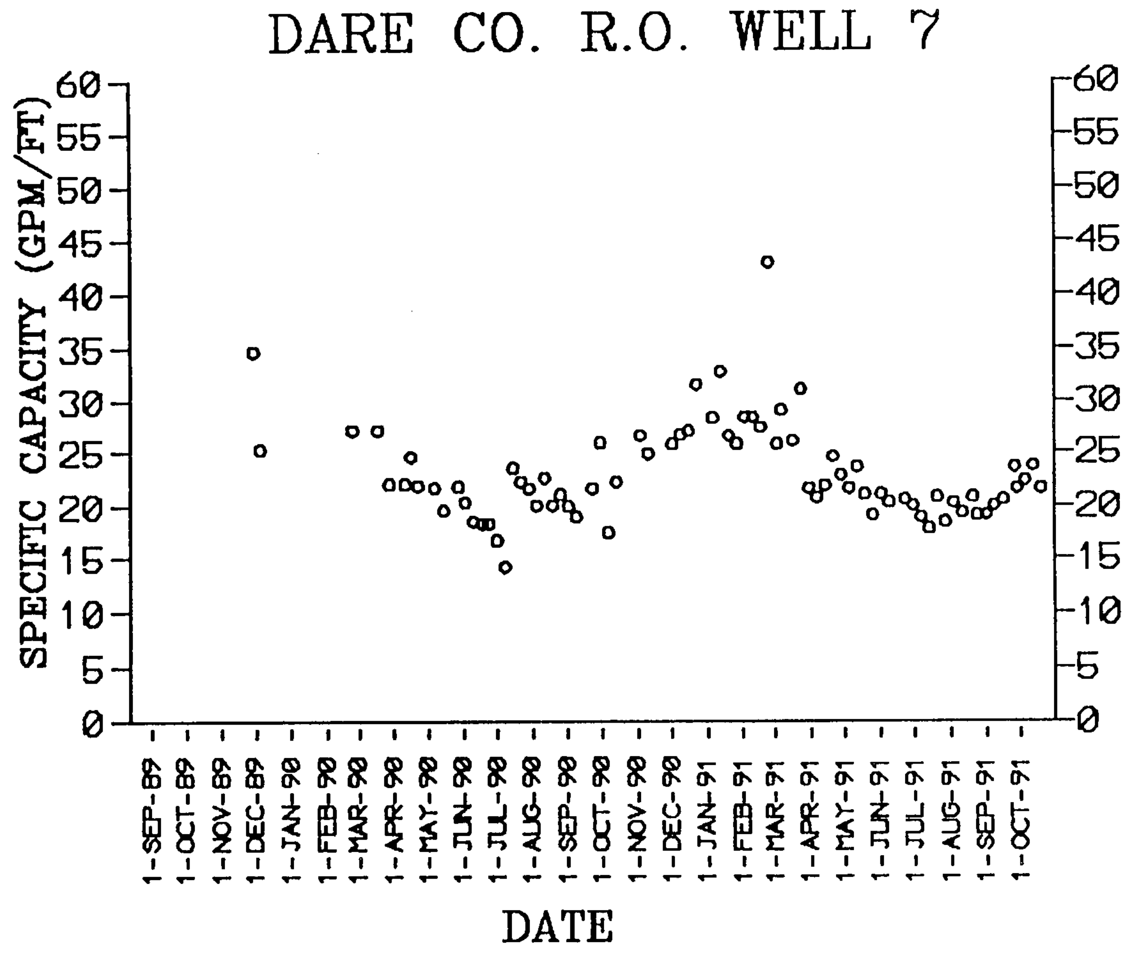

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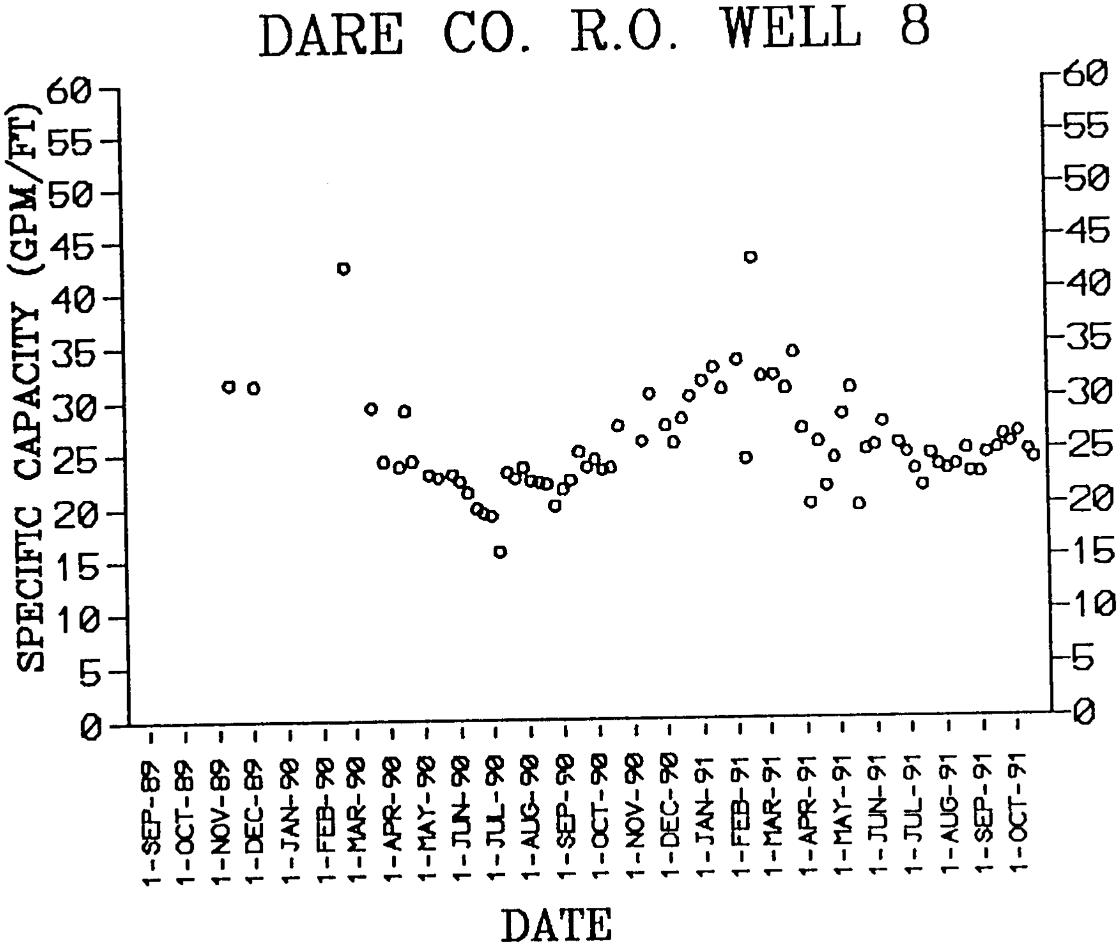
FIGURE A-15. R.O. WELL 7 SPECIFIC CAPACITY VERSUS TIME.



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	PROJECT NAME: DARE COUNTY WELLFIELD	PROJECT NUMBER: CH0-401	

FIGURE A-16. R.O. WELL 8 SPECIFIC CAPACITY VERSUS TIME.

APPENDIX B

TABLE B-1. Depths to static water in the R.O. Supply wellfield

WELL	10/??/89[A]	1/21/90[B]	7/13/90[C]	9/17/91[D]
OCEAN MW	---	---	18.25	23.25
OBS-300	---	---	---	30.5
OBS-600	---	---	---	28
MW-310	---	---	19.0	33.5
MW-410	---	---	18.16	33
MW-510	---	---	20.25	37.5
MW-610	---	---	19.0	38.5
RO WELL 1	21.4	20.0	25.5	27.75
RO WELL 2	21.6	20.4	25.5	26.75
RO WELL 3	18.6	17.5	21.5	24.5
RO WELL 4	18.0	16.5	21.0	23.25
RO WELL 5	19.5	18.0	24.0	26.25
RO WELL 6	20.1	19.0	24.5	---
RO WELL 7	21.0	19.7	25.0	27.25
RO WELL 8	18.6	17.5	22.0	24.25

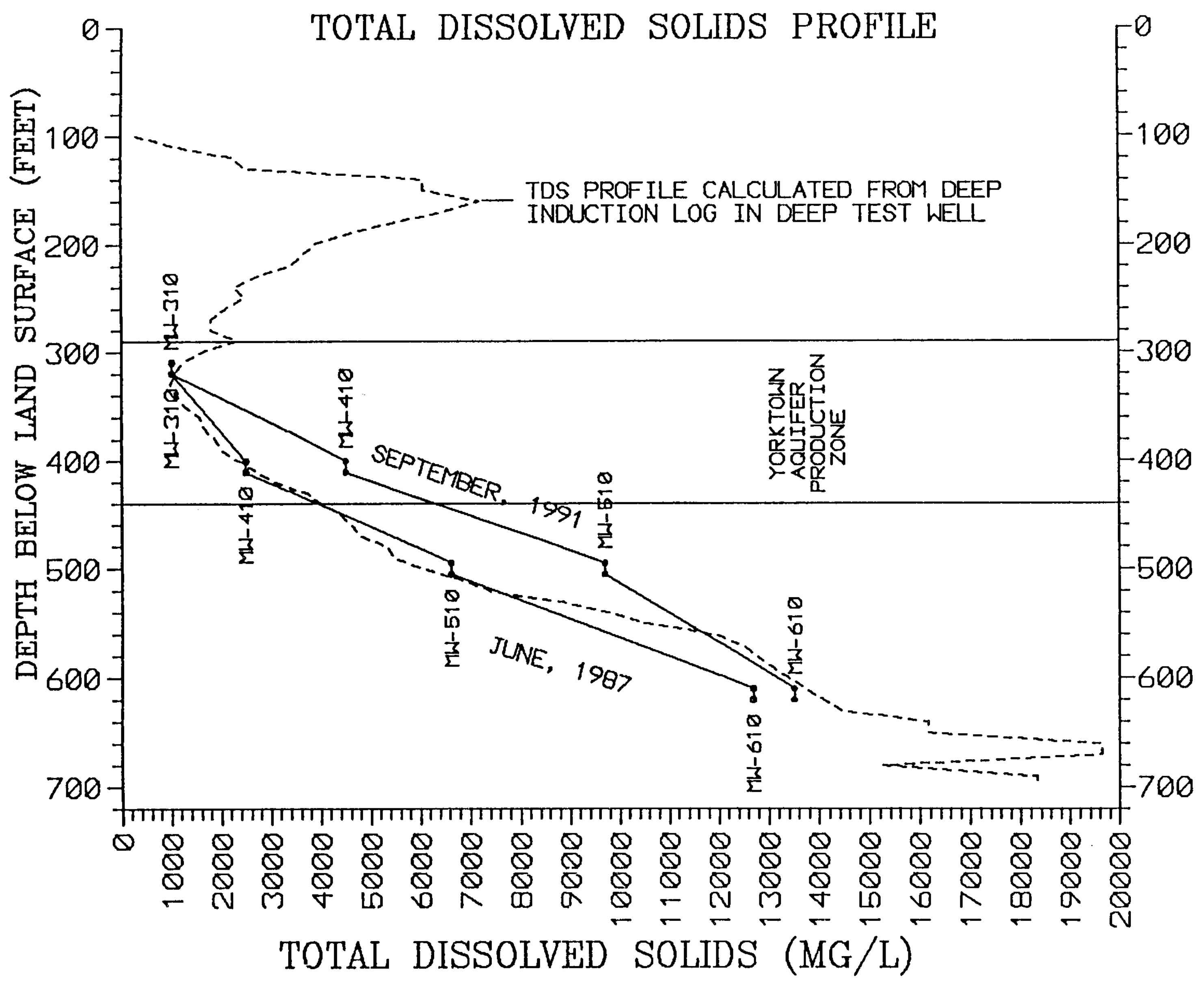
[A] After 6 to 7 hours of recovery.
[B] After 24 hours of recovery.
[C] After 40 hours of recovery
[D] After a 30 hours of recovery with only RO 2 or RO 6 on for flushing; RO 6 on at time of measurements.

TABLE B-2. Numerical parameters and options used in FTWORK model (Version DC053).

MODEL PARAMETER	VALUE
MAXIMUM # OF TIME STEPS	1000
INITIAL TIME STEP SIZE (DAYS)	0.2
MAXIMUM TIME STEP SIZE (DAYS)	5.0
TIME STEP INCREMENTAL MULTIPLIER	1.5
DURATION OF STRESS PERIOD (DAYS)	600
NUMBER OF WELLS	2
LAYERS TO WHICH WELLS ARE OPEN	1 AND 2
MAXIMUM CONC. CHANGE PER TIME STEP (MG/L)	40.
MAXIMUM # OF SSOR ITERATIONS FOR FLOW	1
MAXIMUM # OF NON-LINEAR ITERATIONS FOR FLOW	1
MAXIMUM # OF SSOR ITERATIONS FOR TRANSPORT	20
OVER-RELAXATION FACTOR FOR FLOW	1.95
CONVERGENCE CRITERION FOR FLOW	0.0001
NON-LINEAR WEIGHTING FACTOR FOR FLOW	1.0
NON-LINEAR TOLERANCE FOR HEADS	0.001
OVER-RELAXATION FACTOR FOR TRANSPORT	1.5
CONVERGENCE CRITERION FOR TRANSPORT	0.001
DECAY CONSTANT	0.0
LONGITUDINAL DISPERSIVITY (FT)	5.0
TRANSVERSE DISPERSIVITY (FT)	0.0
RETARDATION FACTOR	1.0
NUMBER OF ACTIVE CELLS	6630
NUMBER OF INACTIVE CELLS	0
NUMBER OF CONSTANT HEAD CELLS	525
WITHDRAWAL RATE (GALLONS/DAY)	858240

OPTIONS USED:

STEADY STATE FLOW
TRANSIENT MODE TRANSPORT
TIME UNITS: DAYS
LENGTH UNITS: FEET
CROSS DERIVATIVES FOR TRANSPORT EXCLUDED
CENTRAL DIFFERENCE WEIGHTING IN SPACE
CENTRAL TIME WEIGHTING
AUTOMATIC CALCULATION OF FLOW EQUATION BANDWIDTH
AUTOMATIC CALCULATION OF TRANSPORT EQUATION BANDWIDTH



M&A *ENVIRONMENTAL AND GROUNDWATER SERVICES*

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PROJECT NAME: DARE COUNTY R.O. PROJECT NUMBER: CHO-401

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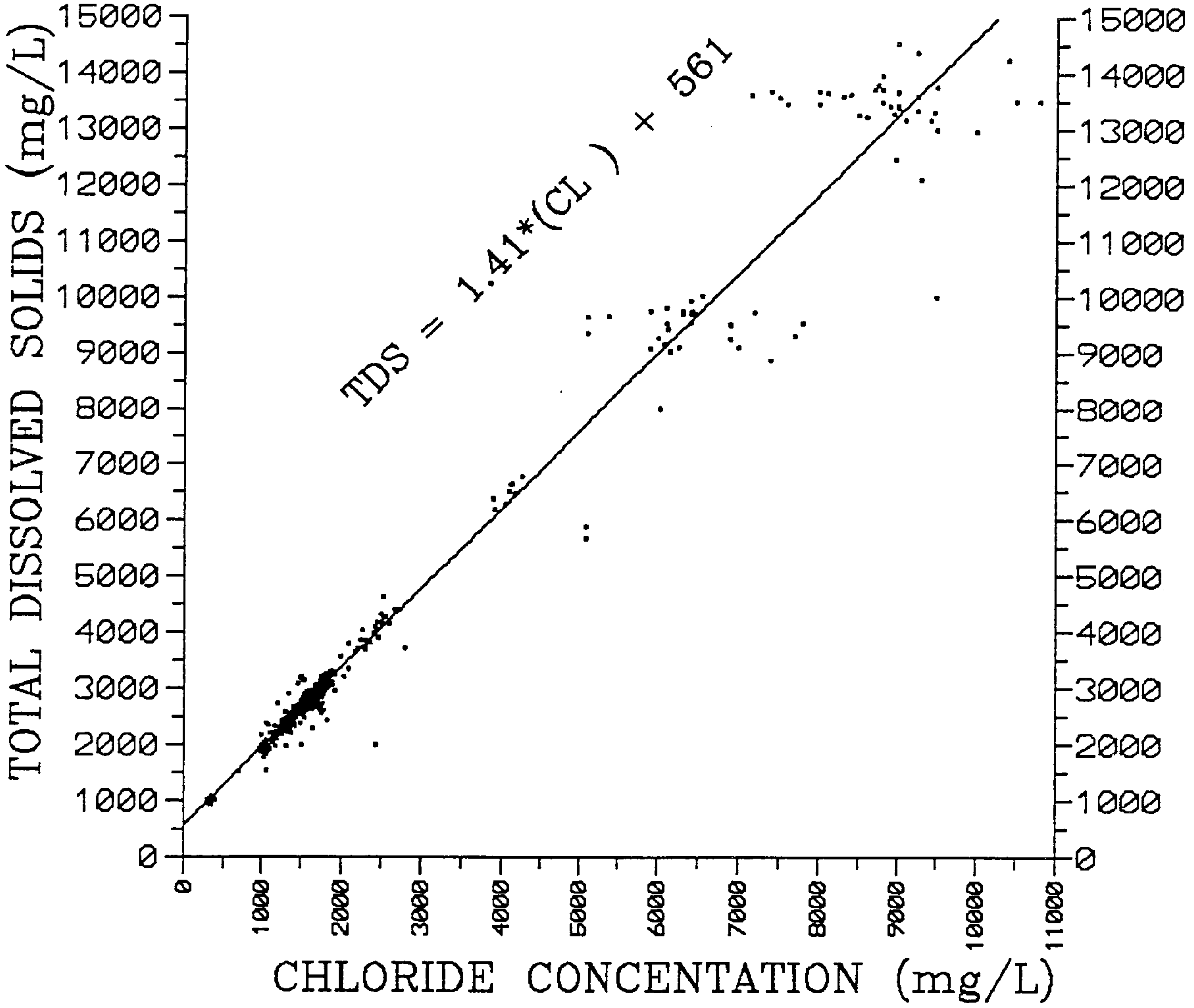
FIGURE B-1. TOTAL DISSOLVED SOLIDS PROFILE BEFORE WELLFIELD START-UP, AND AFTER 2 YEARS OF PUMPING AT AN ANNUAL AVERAGE RATE OF 2.36 MGD.



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	PROJECT NAME: DARE COUNTY R.O. NUMBER: CH0-401	

FIGURE B-2. CHLORIDE CONCENTRATION AS A FUNCTION OF TOTAL DISSOLVED SOLIDS. DATA SET COLLECTED BETWEEN 9/89 AND 10/91.

APPENDIX C

HYDRAULIC MODEL SENSITIVITY ANALYSIS

HYDRAULIC MODEL SENSITIVITY ANALYSIS

A sensitivity analysis was performed using the aquifer parameters determined by the model calibration process to determine the dependency of the predicted heads on the different hydraulic parameters. All sensitivity analysis runs were made using U.S. Geological Survey MODFLOW to run the hydraulics-only version of the model using a withdrawal rate equal to the annual average withdrawal (2.36 MGD) from the Yorktown Aquifer.

Twenty six steady-state model runs were made in which the hydraulic parameters for each layer were systematically changed. The schedule of changes followed this pattern: 1) transmissivity of layer one was doubled; 2) transmissivity of layer one was halved; 3) leakance from layer one to layer two was doubled; 4) leakance from layer one to layer two was halved; 5) leakance from layer one to layer two was multiplied by ten; 6) leakance from layer one to layer two was divided by ten. This cycle was repeated for each layer, with layer five having only the first two in the sequence because it is the lowermost layer and it is not connected by a leakance term to any lower layer.

The sensitivity analysis was designed to bracket the interval of uncertainty for each of the parameters. However, the bracketed intervals used in this analysis are much larger than the probable deviation of the actual aquifer parameters. The calibration process used in this modeling project was designed to minimize the possibility of arriving at a non-unique solution to the configuration of hydraulic parameters, therefore a high level of confidence is placed in the these parameters and the resulting predictions of water quality change.

The sensitivity analysis results were summarized by determining the maximum drawdown in the model grid for each layer for each scenario. The maximum drawdown value occurs in the center of wellfield, in the model cell containing R.O. Well 1. Other measures could be used, such as average drawdown in all eight cells with pumping wells, or an average of the entire wellfield area. However, the maximum drawdown value was chosen as a convenient common reference value, ideally suitable for relative comparisons of the changing hydraulic flow field generated by each parameter change scenario. These maximum drawdown values for all 26 model runs are summarized in table C-1 through C-5 for layers one through five, respectively. For comparative analysis, the equilibrium drawdown values for the hydraulic model, run with no changes to any parameters, are also shown in each table. These tables show the maximum drawdown for each run, the difference between the scenario drawdown and the calibrated model drawdown, and the percent change between the values. Finally, the maximum drawdown values for each layer for each model run are summarized together in Table C-6.

Because of the thorough calibration process and the excellent aquifer performance test data, it is known that the aquifer parameters used are very close to the true conditions in the Yorktown Aquifer. However, the purpose of the sensitivity analysis was to quantify the dependency of predicted results on certain critical model parameters. Critical to the predictions of rate of TDS change made by the model

TABLE C-1. CHANGES TO MODEL LAYER 1 STEADY STATE HEADS RESULTING FROM SYSTEMATIC CHANGES IN THE HYDRAULIC PARAMETERS IN EVERY MODEL LAYER.

MODEL VERSION NUMBER	PARAMETER CHANGE	MAXIMUM DRAWDOWN (FEET)	CHANGE IN DRAWDOWN (FEET)	PERCENT CHANGE (%)
DC059	NO CHANGE	10.93	N/A[A]	N/A
DC060	T_1 * 2	7.91	-3.02	-27.6
DC061	T_1 * 0.5	10.16	-0.77	-7.0
DC062	$L_{1,2}$ * 2	10.91	-0.02	-0.2
DC063	$L_{1,2}$ * 0.5	10.97	0.04	0.4
DC064	$L_{1,2}$ * 10	10.77	-0.16	-1.5
DC065	$L_{1,2}$ * 0.1	DNC[B]	DNC	DNC
DC066	T_2 * 2	5.94	-4.99	-45.7
DC067	T_2 * 0.5	13.13	2.20	20.1
DC068	$L_{2,3}$ * 2	10.74	-0.19	-1.7
DC069	$L_{2,3}$ * 0.5	11.20	0.27	2.5
DC070	$L_{2,3}$ * 10	10.50	-0.43	-3.9
DC071	$L_{2,3}$ * 0.1	12.24	1.31	12.0
DC072	T_3 * 2	10.63	-0.30	-2.7
DC073	T_3 * 0.5	11.06	0.13	1.2
DC074	$L_{3,4}$ * 2	11.13	0.20	1.8
DC075	$L_{3,4}$ * 0.5	10.80	-0.13	-1.2
DC076	$L_{3,4}$ * 10	DNC	DNC	DNC
DC077	$L_{3,4}$ * 0.1	11.90	0.97	8.9
DC078	T_4 * 2	10.42	-0.51	-4.7
DC079	T_4 * 0.5	11.23	0.30	2.7
DC080	$L_{4,5}$ * 2	10.92	-0.01	-0.1
DC081	$L_{4,5}$ * 0.5	10.96	0.03	0.3
DC082	$L_{4,5}$ * 10	10.89	-0.04	-0.4
DC083	$L_{4,5}$ * 0.1	11.15	0.22	2.0
DC084	T_5 * 2	9.72	-1.21	-11.1
DC085	T_5 * 0.5	11.92	.99	9.1

NOTES:

[A] Not applicable. All changes reported below are relative to the drawdown value for model version DC059.

[B] Did not converge. The parameter change resulted in an unstable configuration which U.S. Geological Survey MODFLOW could not numerically iterate to a stable solution.

Aquifer parameter symbols use the following subscript notation:

T_1 = Transmissivity of layer 1.

$L_{1,2}$ = Leakance between layers 1 and 2.

TABLE C-2. CHANGES TO MODEL LAYER 2 STEADY STATE HEADS RESULTING FROM SYSTEMATIC CHANGES IN THE HYDRAULIC PARAMETERS IN EVERY MODEL LAYER.

MODEL VERSION NUMBER	PARAMETER CHANGE	MAXIMUM DRAWDOWN (FEET)	CHANGE IN DRAWDOWN (FEET)	PERCENT CHANGE (%)
DC059	AS CALIBRATED	10.89	N/A[A]	N/A
DC060	$T_1 * 2$	7.86	-3.03	-27.8
DC061	$T_1 * 0.5$	10.13	-0.76	-7.0
DC062	$L_{1,2} * 2$	10.88	-0.01	-0.1
DC063	$L_{1,2} * 0.5$	10.89	0.00	0.0
DC064	$L_{1,2} * 10$	10.77	-0.12	-1.1
DC065	$L_{1,2} * 0.1$	DNC[B]	DNC	DNC
DC066	$T_2 * 2$	5.96	-4.93	-45.3
DC067	$T_2 * 0.5$	13.04	2.15	19.7
DC068	$L_{2,3} * 2$	10.68	-0.21	-1.9
DC069	$L_{2,3} * 0.5$	11.17	0.28	2.6
DC070	$L_{2,3} * 10$	10.42	-0.47	-4.3
DC071	$L_{2,3} * 0.1$	12.23	1.34	12.3
DC072	$T_3 * 2$	10.58	-0.31	-2.8
DC073	$T_3 * 0.5$	11.02	0.13	1.2
DC074	$L_{3,4} * 2$	11.09	0.20	1.8
DC075	$L_{3,4} * 0.5$	10.75	-0.14	-1.3
DC076	$L_{3,4} * 10$	DNC	DNC	DNC
DC077	$L_{3,4} * 0.1$	11.88	0.99	9.1
DC078	$T_4 * 2$	10.37	-0.52	-4.8
DC079	$T_4 * 0.5$	11.19	0.30	2.8
DC080	$L_{4,5} * 2$	10.88	-0.01	-0.1
DC081	$L_{4,5} * 0.5$	10.92	0.03	0.3
DC082	$L_{4,5} * 10$	10.84	-0.05	-0.5
DC083	$L_{4,5} * 0.1$	11.11	0.22	2.0
DC084	$T_5 * 2$	9.67	-1.22	-11.2
DC085	$T_5 * 0.5$	11.96	1.07	9.8

NOTES:

[A] Not applicable. All changes reported below are relative to the drawdown value for model version DC059.

[B] Did not converge. The parameter change resulted in an unstable configuration which U.S. Geological Survey MODFLOW could not numerically iterate to a stable solution.

Aquifer parameter symbols use the following subscript notation:

T_1 = Transmissivity of layer 1.

$L_{1,2}$ = Leakance between layers 1 and 2.

TABLE C-3. CHANGES TO MODEL LAYER 3 STEADY STATE HEADS RESULTING FROM SYSTEMATIC CHANGES IN THE HYDRAULIC PARAMETERS IN EVERY MODEL LAYER.

MODEL VERSION NUMBER	PARAMETER CHANGE	MAXIMUM DRAWDOWN (FEET)	CHANGE IN DRAWDOWN (FEET)	PERCENT CHANGE (%)
DC059	AS CALIBRATED	6.69	N/A[A]	N/A
DC060	T_1 * 2	4.65	-2.04	-30.5
DC061	T_1 * 0.5	5.36	-1.33	-19.9
DC062	$L_{1,2}$ * 2	6.68	-0.01	-0.1
DC063	$L_{1,2}$ * 0.5	6.69	0.00	0.0
DC064	$L_{1,2}$ * 10	6.56	-0.13	-1.9
DC065	$L_{1,2}$ * 0.1	DNC[B]	DNC	DNC
DC066	T_2 * 2	3.45	-3.24	-48.4
DC067	T_2 * 0.5	6.93	0.24	3.6
DC068	$L_{2,3}$ * 2	7.13	0.44	6.6
DC069	$L_{2,3}$ * 0.5	6.12	-0.57	-8.5
DC070	$L_{2,3}$ * 10	7.81	1.12	16.7
DC071	$L_{2,3}$ * 0.1	4.62	-2.07	-30.9
DC072	T_3 * 2	6.22	-0.47	-7.0
DC073	T_3 * 0.5	6.95	0.26	3.9
DC074	$L_{3,4}$ * 2	7.06	0.37	5.5
DC075	$L_{3,4}$ * 0.5	6.40	-0.29	-4.3
DC076	$L_{3,4}$ * 10	DNC	DNC	DNC
DC077	$L_{3,4}$ * 0.1	8.26	1.57	23.5
DC078	T_4 * 2	6.10	-0.59	-8.8
DC079	T_4 * 0.5	7.02	0.33	4.9
DC080	$L_{4,5}$ * 2	6.65	-0.04	-0.6
DC081	$L_{4,5}$ * 0.5	6.74	0.05	0.7
DC082	$L_{4,5}$ * 10	6.61	-0.08	-1.2
DC083	$L_{4,5}$ * 0.1	7.04	0.35	5.2
DC084	T_5 * 2	5.35	-1.34	-20.0
DC085	T_5 * 0.5	7.85	1.16	17.3

NOTES:

[A] Not applicable. All changes reported below are relative to the drawdown value for model version DC059.

[B] Did not converge. The parameter change resulted in an unstable configuration which U.S. Geological Survey MODFLOW could not numerically iterate to a stable solution.

Aquifer parameter symbols use the following subscript notation:

T_1 = Transmissivity of layer 1.

$L_{1,2}$ = Leakance between layers 1 and 2.

TABLE C-4. CHANGES TO MODEL LAYER 4 STEADY STATE HEADS RESULTING FROM SYSTEMATIC CHANGES IN THE HYDRAULIC PARAMETERS IN EVERY MODEL LAYER.

MODEL VERSION NUMBER	PARAMETER CHANGE	MAXIMUM DRAWDOWN (FEET)	CHANGE IN DRAWDOWN (FEET)	PERCENT CHANGE (%)
DC059	AS CALIBRATED	5.56	N/A[A]	N/A
DC060	T_1 * 2	3.79	-1.77	-31.8
DC061	T_1 * 0.5	4.20	-1.36	-24.5
DC062	$L_{1,2}$ * 2	5.55	-0.01	-0.2
DC063	$L_{1,2}$ * 0.5	5.56	0.00	0.0
DC064	$L_{1,2}$ * 10	5.43	-0.13	-2.3
DC065	$L_{1,2}$ * 0.1	DNC[B]	DNC	DNC
DC066	T_2 * 2	2.79	-2.77	-49.8
DC067	T_2 * 0.5	5.47	-0.09	-1.6
DC068	$L_{2,3}$ * 2	5.75	0.19	3.4
DC069	$L_{2,3}$ * 0.5	5.25	-0.31	-5.6
DC070	$L_{2,3}$ * 10	5.91	0.35	6.3
DC071	$L_{2,3}$ * 0.1	4.24	-1.32	-23.7
DC072	T_3 * 2	5.23	-0.33	-5.9
DC073	T_3 * 0.5	5.70	0.14	2.5
DC074	$L_{3,4}$ * 2	5.28	-0.28	-5.0
DC075	$L_{3,4}$ * 0.5	5.74	0.18	3.2
DC076	$L_{3,4}$ * 10	DNC	DNC	DNC
DC077	$L_{3,4}$ * 0.1	4.28	-1.28	-23.0
DC078	T_4 * 2	4.89	-0.67	-12.1
DC079	T_4 * 0.5	5.95	0.39	7.0
DC080	$L_{4,5}$ * 2	5.51	-0.05	-0.9
DC081	$L_{4,5}$ * 0.5	5.64	0.08	1.4
DC082	$L_{4,5}$ * 10	5.44	-0.12	-2.2
DC083	$L_{4,5}$ * 0.1	6.08	0.52	9.4
DC084	T_5 * 2	4.07	-1.49	-26.8
DC085	T_5 * 0.5	6.87	1.31	23.6

NOTES:

[A] Not applicable. All changes reported below are relative to the drawdown value for model version DC059.

[B] Did not converge. The parameter change resulted in an unstable configuration which U.S. Geological Survey MODFLOW could not numerically iterate to a stable solution.

Aquifer parameter symbols use the following subscript notation:

T_1 = Transmissivity of layer 1.

$L_{1,2}$ = Leakance between layers 1 and 2.

TABLE C-5. CHANGES TO MODEL LAYER 5 STEADY STATE HEADS RESULTING FROM SYSTEMATIC CHANGES IN THE HYDRAULIC PARAMETERS IN EVERY MODEL LAYER.

MODEL VERSION NUMBER	PARAMETER CHANGE	MAXIMUM DRAWDOWN (FEET)	CHANGE IN DRAWDOWN (FEET)	PERCENT CHANGE (%)
DC059	AS CALIBRATED	5.36	N/A[A]	N/A
DC060	T_1 * 2	3.64	-1.72	-32.1
DC061	T_1 * 0.5	3.99	-1.37	-25.6
DC062	$L_{1,2}$ * 2	5.35	-0.01	-0.2
DC063	$L_{1,2}$ * 0.5	5.36	0.00	0.0
DC064	$L_{1,2}$ * 10	5.23	-0.13	-2.4
DC065	$L_{1,2}$ * 0.1	DNC[B]	DNC	DNC
DC066	T_2 * 2	2.67	-2.69	-50.2
DC067	T_2 * 0.5	5.22	-0.14	-2.6
DC068	$L_{2,3}$ * 2	5.52	0.16	3.0
DC069	$L_{2,3}$ * 0.5	5.09	-0.27	-5.0
DC070	$L_{2,3}$ * 10	5.64	0.28	5.2
DC071	$L_{2,3}$ * 0.1	4.17	-1.19	-22.2
DC072	T_3 * 2	5.05	-0.31	-5.8
DC073	T_3 * 0.5	5.49	0.13	2.4
DC074	$L_{3,4}$ * 2	5.12	-0.24	-4.5
DC075	$L_{3,4}$ * 0.5	5.51	0.15	2.8
DC076	$L_{3,4}$ * 10	DNC	DNC	DNC
DC077	$L_{3,4}$ * 0.1	4.20	-1.16	-21.6
DC078	T_4 * 2	4.73	-0.63	-11.8
DC079	T_4 * 0.5	5.73	0.37	6.9
DC080	$L_{4,5}$ * 2	5.41	0.05	0.9
DC081	$L_{4,5}$ * 0.5	5.27	-0.09	-1.7
DC082	$L_{4,5}$ * 10	5.42	0.06	1.1
DC083	$L_{4,5}$ * 0.1	4.85	-0.51	-9.5
DC084	T_5 * 2	3.84	-1.55	-28.9
DC085	T_5 * 0.5	6.73	1.37	25.6

NOTES:

[A] Not applicable. All changes reported below are relative to the drawdown value for model version DC059.

[B] Did not converge. The parameter change resulted in an unstable configuration which U.S. Geological Survey MODFLOW could not numerically iterate to a stable solution.

Aquifer parameter symbols use the following subscript notation:

T_1 = Transmissivity of layer 1.

$L_{1,2}$ = Leakance between layers 1 and 2.

TABLE C-6. SUMMARY OF MAXIMUM DRAWDOWN VALUES FOR EACH LAYER FOR ALL SENSITIVITY ANALYSIS MODEL RUNS.

MODEL VERSION NUMBER	PARAMETER CHANGE	MAXIMUM DRAWDOWN (FEET)				
		LAYER 1	LAYER 2	LAYER 3	LAYER 4	LAYER 5
DC059	NO CHANGE	10.93	10.89	6.69	5.56	5.36
DC060	T_1 * 2.0	7.91	7.86	4.65	3.79	3.64
DC061	T_1 * 0.5	10.16	10.13	5.36	4.20	3.99
DC062	$L_{1,2}$ * 2.0	10.91	10.88	6.68	5.55	5.35
DC063	$L_{1,2}$ * 0.5	10.97	10.89	6.69	5.56	5.36
DC064	$L_{1,2}$ * 10.	10.77	10.77	6.56	5.43	5.23
DC065	$L_{1,2}$ * 0.1	DNC[B]	DNC	DNC	DNC	DNC
DC066	T_2 * 2.0	5.94	5.96	3.45	2.79	2.67
DC067	T_2 * 0.5	13.13	13.04	6.93	5.47	5.22
DC068	$L_{2,3}$ * 2.0	10.74	10.68	7.13	5.75	5.52
DC069	$L_{2,3}$ * 0.5	11.20	11.17	6.12	5.25	5.09
DC070	$L_{2,3}$ * 10.	10.50	10.42	7.81	5.91	5.64
DC071	$L_{2,3}$ * 0.1	12.24	12.23	4.62	4.24	4.17
DC072	T_3 * 2.0	10.63	10.58	6.22	5.23	5.05
DC073	T_3 * 0.5	11.06	11.02	6.95	5.70	5.49
DC074	$L_{3,4}$ * 2.0	11.13	11.09	7.06	5.28	5.12
DC075	$L_{3,4}$ * 0.5	10.80	10.75	6.40	5.74	5.51
DC076	$L_{3,4}$ * 10.	DNC[B]	DNC	DNC	DNC	DNC
DC077	$L_{3,4}$ * 0.1	11.90	11.88	8.26	4.28	4.20
DC078	T_4 * 2.0	10.42	10.37	6.10	4.89	4.73
DC079	T_4 * 0.5	11.23	11.19	7.02	5.95	5.73
DC080	$L_{4,5}$ * 2.0	10.92	10.88	6.65	5.51	5.41
DC081	$L_{4,5}$ * 0.5	10.96	10.92	6.74	5.64	5.27
DC082	$L_{4,5}$ * 10.	10.89	10.84	6.61	5.44	5.42
DC083	$L_{4,5}$ * 0.1	11.15	11.11	7.04	6.08	4.85
DC084	T_5 * 2.0	9.72	9.67	5.35	4.07	3.81
DC085	T_5 * 0.5	11.92	11.96	7.85	6.87	6.73

NOTES: Aquifer parameter symbols use the following subscript notation:

T_1 = Transmissivity of layer 1.

$L_{1,2}$ = Leakance between layers 1 and 2.

[B] DNC = Model run did not converge; no value for this scenario.

are the leakance terms describing the hydraulic connection between the Yorktown Aquifer and the mid-Yorktown aquitard, and between the Yorktown Aquifer and the lower-Yorktown Aquifer. The vertical leak<u>age</u> across these layers plays a role in controlling the rate of water quality degradation and is to a large degree dependent upon the leak<u>ance</u> terms connecting these layers. Therefore, an analysis was made of their interdependence. Table C-7 summarizes the rates of leakage from the mid-Yorktown aquitard upwards to the production zone for various sets of aquifer parameter modifications, all reported relative to the leakage rate predicted by the calibrated model.

It can be seen in Table C-7 that the upward leakage of groundwater to model layer two from layer three (mid-Yorktown aquitard to the production zone) changes according to changes in the aquifer parameters. Of interest are the effects of changes to the leakance parameter between these two layers, because this is the term which is most difficult to determine from aquifer tests. The leakance term was changed in runs DC068 through DC071, and the factor of change is marked with a superscript "A" in column seven. A similar comparison was made of the leakage rate between the production zone and the top of the lower-Yorktown aquifer (model layer 2 to layer 4; see Table C-8).

The results of the sensitivity analysis indicate that the rate of vertical leakage from underlying aquifers upwards into the Yorktown production zone is very sensitive to the leakance parameters between layer two and layers three and four. The leakance parameters used for the intervals between layers two/three and three/four

TABLE C-7. SUMMARY OF EFFECTS OF PARAMETER CHANGES ON THE VERTICAL LEAKAGE FROM THE MID-YORKTOWN AQUITARD (LAYER 3) TO THE PRODUCTION ZONE (LAYERS 1 AND 2).

Model version number	Parameter change	Maximum Drawdown (feet)		Difference in maximum drawdown (feet)	Fraction of version DC059	Factor of change in leakance between Layer 2 and Layer 3	Factor of change in vertical leakage between Layer 2 and Layer 3
		Average production zone	Layer 3 mid-Yorktown aquitard				
DC059	NO CHANGE	10.91	6.69	4.22	N/A	N/A	N/A
DC060	T_1 * 2.0	7.89	4.65	3.24	0.77	1.00	0.77
DC061	T_1 * 0.5	10.15	5.36	4.79	1.13	1.00	1.13
DC062	$L_{1,2}$ * 2.0	10.90	6.68	4.22	1.00	1.00	1.00
DC063	$L_{1,2}$ * 0.5	10.93	6.69	4.24	1.00	1.00	1.00
DC064	$L_{1,2}$ * 10.	10.77	6.56	4.21	1.00	1.00	1.00
DC065	$L_{1,2}$ * 0.1	DNC[B]	DNC	DNC	DNC	DNC	DNC
DC066	T_2 * 2.0	5.95	3.45	2.50	0.59	1.00	0.59
DC067	T_2 * 0.5	13.09	6.93	6.16	1.46	1.00	1.46
DC068	$L_{2,3}$ * 2.0	10.71	7.13	3.58	0.85	2.00[A]	1.70
DC069	$L_{2,3}$ * 0.5	11.19	6.12	5.07	1.20	0.50[A]	0.60
DC070	$L_{2,3}$ * 10.	10.46	7.81	2.65	0.63	10.00[A]	6.28
DC071	$L_{2,3}$ * 0.1	12.24	4.62	7.62	1.80	0.10[A]	0.18
DC072	T_3 * 2.0	10.61	6.22	4.39	1.04	1.00	1.04
DC073	T_3 * 0.5	11.04	6.95	4.09	0.97	1.00	0.97
DC074	$L_{3,4}$ * 2.0	11.11	7.06	4.05	0.96	1.00	0.96
DC075	$L_{3,4}$ * 0.5	10.78	6.40	4.38	1.04	1.00	1.04
DC076	$L_{3,4}$ * 10.	DNC[B]	DNC	DNC	DNC	DNC	DNC
DC077	$L_{3,4}$ * 0.1	11.89	8.26	3.63	0.86	1.00	0.86
DC078	T_4 * 2.0	10.40	6.10	4.30	1.02	1.00	1.02
DC079	T_4 * 0.5	11.21	7.02	4.19	0.99	1.00	0.99
DC080	$L_{4,5}$ * 2.0	10.90	6.65	4.25	1.01	1.00	1.01
DC081	$L_{4,5}$ * 0.5	10.94	6.74	4.20	1.00	1.00	1.00
DC082	$L_{4,5}$ * 10.	10.87	6.61	4.26	1.01	1.00	1.01
DC083	$L_{4,5}$ * 0.1	11.13	7.04	4.09	0.97	1.00	0.97
DC084	T_5 * 2.0	9.70	5.35	4.35	1.03	1.00	1.03
DC085	T_5 * 0.5	11.94	7.85	4.09	0.97	1.00	0.97

NOTES: [A] Factor change to the leakance term between layers 2 and 3 for this scenario.

[B] DNC = Model run did not converge; no value for this scenario.

TABLE C-8. SUMMARY OF EFFECTS OF PARAMETER CHANGES ON THE VERTICAL LEAKAGE FROM THE LOWER-YORKTOWN AQUIFER (LAYER 4) TO THE PRODUCTION ZONE (LAYERS 1 AND 2).

Model version number	Parameter change	Maximum Drawdown (feet)		Difference in maximum drawdown (feet)	Fraction of version DC059	Factor of change in leakance between Layer 2 and Layer 4	Factor of change in vertical leakage between Layer 2 and Layer 4
		Average production zone	Layer 4 lower-Yorktown aquifer				
DC059	NO CHANGE	10.91	5.56	5.35	N/A	N/A	N/A
DC060	T_1 * 2.0	7.89	3.79	4.10	0.77	1.00	0.77
DC061	T_1 * 0.5	10.15	4.20	5.95	1.11	1.00	1.11
DC062	$L_{1,2}$ * 2.0	10.90	5.55	5.35	1.00	1.00	1.00
DC063	$L_{1,2}$ * 0.5	10.93	5.56	5.37	1.00	1.00	1.00
DC064	$L_{1,2}$ * 10.	10.77	5.43	5.34	1.00	1.00	1.00
DC065	$L_{1,2}$ * 0.1	DNC[B]	DNC	DNC	DNC	DNC	DNC
DC066	T_2 * 2.0	5.95	2.79	3.16	0.59	1.00	0.59
DC067	T_2 * 0.5	13.09	5.47	7.62	1.42	1.00	1.42
DC068	$L_{2,3}$ * 2.0	10.71	5.75	4.96	0.93	1.33[A]	1.24
DC069	$L_{2,3}$ * 0.5	11.19	5.25	5.94	1.11	0.67[A]	0.74
DC070	$L_{2,3}$ * 10.	10.46	5.91	4.55	0.85	1.82[A]	1.55
DC071	$L_{2,3}$ * 0.1	12.24	4.24	8.00	1.49	0.18[A]	0.27
DC072	T_3 * 2.0	10.61	5.23	5.38	1.00	1.00	1.00
DC073	T_3 * 0.5	11.04	5.70	5.34	1.00	1.00	1.00
DC074	$L_{3,4}$ * 2.0	11.11	5.28	5.83	1.09	1.33[A]	1.45
DC075	$L_{3,4}$ * 0.5	10.78	5.74	5.04	0.94	0.67[A]	0.63
DC076	$L_{3,4}$ * 10.	DNC[B]	DNC	DNC	DNC	DNC	DNC
DC077	$L_{3,4}$ * 0.1	11.89	4.28	7.61	1.42	0.18[A]	0.26
DC078	T_4 * 2.0	10.40	4.89	5.51	1.03	1.00	1.03
DC079	T_4 * 0.5	11.21	5.95	5.26	0.98	1.00	0.98
DC080	$L_{4,5}$ * 2.0	10.90	5.51	5.39	1.01	1.00	1.01
DC081	$L_{4,5}$ * 0.5	10.94	5.64	5.30	0.99	1.00	0.99
DC082	$L_{4,5}$ * 10.	10.87	5.44	5.43	1.01	1.00	1.01
DC083	$L_{4,5}$ * 0.1	11.13	6.08	5.05	0.94	1.00	0.94
DC084	T_5 * 2.0	9.70	4.07	5.63	1.05	1.00	1.05
DC085	T_5 * 0.5	11.94	6.87	5.07	0.95	1.00	0.95

NOTES: [A] Factor change to the leakance term between layers 2 and 4 for this scenario.

[B] DNC = Model run did not converge; no value for this scenario.

were determined based on both detailed lithologic logs and through an iterative model calibration process during which known TDS concentration rates-of-change were used to constrain the leakance values. This is a sound approach, and the resulting long term predictions of water quality change are considered to be very reliable. However, several of the leakance parameters are estimates based on lithology, and the effective porosity values used were taken from literature sources for typical fine-sand and clayey-sand lithologies. In a solute transport model these two variables interact in a manner that if either one differs from the true subsurface value the possibility of a non-unique model calibration solution does exist. To improve the reliability of the solute transport model predictions, additional aquifer performance testing of the lower-Yorktown aquifer and mid-Yorktown aquitard would have to be performed to verify the vertical hydraulic conductivities for these units.

The sensitivity analysis also indicates that the leakage rates upwards to the production interval are moderately sensitive to the transmissivity parameters for the production zone. However, the values for transmissivity in the production zone are known with the highest level of confidence. These values have been verified by multiple aquifer performance tests, by steady state analytical modeling of the summer/winter head changes, and by a transient-mode simulated aquifer test using a numerical model.

The vertical leakage rates into the production zone were found to be insensitive to leakance parameter changes between layers four and five, or to transmissivity parameter changes in layers three, four, or five. Therefore, possible differences between the actual subsurface conditions and the values used for these parameters would have only a minimal impact on the results of the predictive modeling.