Investigation of Surface Water-Groundwater Interactions at S-7 Pump Station

Broward and Palm Beach Counties, Florida

Technical Publication WS-11

Steven Krupa, P.G., and Steven Hill, SFWMD
Sandrine Diaz, Ecole Nationale, du genie del'eau et de l'environment ENGEES

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South Florida Water Management District
3301 Gun Club Road
West Palm Beach, FL 33306
(561) 686-8800
www.sfwmd.gov

Excerpted from the Everglades Program Management Plan Research and Monitoring Project 3 (RAM-3)

EXECUTIVE SUMMARY

In 1994, the State of Florida enacted the Everglades Forever Act (EFA) as a result of federal legislation. Later in that year, the South Florida Water Management District (SFWMD) and the Florida Department of Environmental Protection (FDEP) were directed to develop a program management plan to implement the EFA. As a part of this management plan, the SFWMD and FDEP developed individual action plans for each of the 55 projects that comprise the Everglades program.

The SFWMD and the FDEP consolidated the requirements of the EFA into a number of major elements, including the research and monitoring (RAM) element. This element contained the projects focusing on the evaluation of water quality. The initial project, RAM-1, Description of Water Quality in the Everglades Protection Area and Tributary Waters, was awarded to Limno-Tech, Inc. (LTI) under Contract C-5242. The objective of RAM-1 was to evaluate water quality using information contained in the SFWMD databases and compare the findings to state water quality standards (Chapter 62-302.530, Florida Administrative Code [F.A.C.]).

RAM-1 was considered complete on September 15, 1995, when LTI distributed its report, *Data Analysis in Support of the Everglades Forever Act*. This report was then used by SFWMD staff to begin work on RAM-3, with the primary objective being to evaluate in greater detail the spatial and temporal nature of the water quality deviations identified in the LTI report. Deviations represent specific Class III water quality criteria that are exceeded in a sampling event. A secondary RAM-3 objective was to determine if deviation causes could be identified and, if so, to determine if the causes were the result of natural processes or human activities.

The analysis of the water quality data for RAM-3 focused on dissolved oxygen (DO) and specific conductance (SC). It was found that DO deviations (readings less than 5 milligrams/liter [mg/l]) and SC deviations (readings greater than 1,275 microseconds/centimeter [µS/cm]) were regularly occurring throughout the SFWMD with the majority of the deviations appearing at SFWMD pump stations. A further review of the data was completed for the period of 1979 to 1983 at pump stations S-5A, S-6, S-7, S-8, S-140, and S-332. Dissolved oxygen deviations occurred both in the dry (November to May) and wet seasons (June to October), with a greater number of deviations occurring in the wet season (average = 133.3) than in the dry season (average = 80.8). Specific conductivity deviations were the most frequent in the wet season at S-6, whereas the dry season produced the greater number of deviations at S-5A and S-7.

It was decided to complete a more detailed investigation at Pump Stations S-5A, S-6, or S-7, the sites that had shown the greatest number of deviations, to better understand the reasons for the deviations. This detailed investigation would include the acquisition of new data to obtain a better picture of water movement. To minimize equipment costs to the SFWMD, existing monitor equipment at these pump stations was inventoried and new equipment needs were identified. Based on the equipment cost factors, pump station S-7 was selected for an in-depth analysis. The monitor equipment at S-7 included electronic headwater and tailwater water level recorders, a rain gage, on-site monitor wells, and ultrasonic velocity meters (UVM). Additionally, the pump operations equipment was included in the project.

The objectives of the detailed investigation at S-7 were as follows:

- Assess the effect of pumping activity on surface and groundwater levels
- Estimate the interaction between the surface water and the groundwater
- Determine if the pump station activity degrades or improves the surface water and/or the groundwater quality

If it was determined that pump station activity caused water quality degradation, the investigation would then attempt to determine if the degradation was abatable through a change in pump station activity. The authorization to proceed with this investigation was received from the FDEP in August 1995. The field data for this project were collected from September 13, 1995, to November 7, 1995.

- The S-7 Pump Station, located on State Road 27 at the Palm Beach - Broward County border, bridges the North New River Canal, and pumps from the Everglades Agricultural Area into Water Conservation Area 2A. The cross-section of the headwater canal 223 feet north of the pump station is 17 feet deep, while the tailwater is 13.5 feet deep 149 feet to the south. On November 15, 1995, the headwater level was 10.82 feet NGVD and the tailwater level was 13.58 feet NGVD. The pump station includes three horizontal pumps rated at 830 cubic feet second (cfs) each, with a combined total production of 2,490 cfs, and one spillway. The maximum operating head difference between the headwater and tailwater elevations is set at 5.3 feet. This pump station is semi-automated and is staffed during daylight hours and extreme meteorological events.
- Information obtained from the RAM-1 report (LTI, 1995) indicated that the largest number of deviations at S-7 were for DO and SC. Therefore, these parameters were the focus of the investigation. Headwater stage, tailwater stage, groundwater level, and water quality parameters were measured using In-Situ, Inc., pressure transducers and water quality sensors in the groundwater wells. Hydrolab™ water quality sensors were installed to measure pH, as well as the SC, temperature, DO, and total dissolved solids of both the headwater and tailwater sections of the structure.
- The results show the DO levels in both the headwater and tailwater were chronically low, with the tailwater levels slightly higher. During the investigation the mean engine revolutions per minute (rpm) was 496 with a maximum of 2,040 rpm. The headwater mean DO was 0.59 mg/l (n = 3,284), while the tailwater mean DO was 0.77 mg/l (n = 3,023). The minimum DO readings recorded at both the headwater and tailwater sides of the pump station were at or near the sensor detection limit (0.0400 mg/l). The maximum DO readings were 1.84 mg/l on the headwater side and 2.52 mg/l on the tailwater side.

The lowest DO levels occurred in the headwater when the pumps were off and underflow beneath the structure was at a maximum. Underflow occurs when groundwater is moving under the structure and into the headwater side of the pump station. This was demonstrated in the UVM profiles of the headwater side of the pump station, combined with concurrent DO readings. Pumping was shown to elevate the DO levels from 0.25 to 0.75 mg/l in the immediate vicinity of the pump station, primarily due to turbulence-induced aeration.

The elevations of groundwater and surface water were analyzed to determine relationships to DO levels. The water elevation of the shallow groundwater well elevations was found to be inversely related to the DO levels in the headwater side of the structure. The correlation of the shallow groundwater well elevations and the headwater DO was -0.3645. The elevation of the deep groundwater well seemed to have less correlation with DO levels, indicating the surface water interaction is primarily with the shallow surficial aquifer.

Hand measurements indicated that vertical stratification of DO and SC was occurring in the top one to two feet of water, and that DO is inversely related with depth, while SC was directly related to depth. This stratification occurs when the headwater pumps are not operating and mixing. Turnover or mixing occurs during pumping events. Low DO and high SC values in the deep surface water are likely caused by large groundwater inflows that do not mix with the upper water when the pump is off.

The SC of the headwater was inversely related to water levels in the shallow well. Water levels within the shallow aquifer are a function of rainfall and runoff; as the water level rises in the shallow aquifer from rainfall infiltration, gradients increase between the shallow well and the canal. Surface water inflow also increases from rainfall and additional upstream runoff, diluting the higher conductivity groundwater that has entered the canal. Elevated SC was positively correlated with water velocities from incoming surface waters during pumping activity. The SC of the deep well correlated to the shallow well SC (0.6501) and was inversely related to the tailwater level (-0.322) and the deep well water level (-0.2346). This relationship was also supported by the upward groundwater gradients on the headwater side of the pump station.

As a result of the field investigation, it was determined that the operation of the S-7 Pump Station caused significant mixing of groundwater and surface water in the headwater side of the pump station. This groundwater appears to emanate from both the shallow and deep wells combined with groundwater upstream. Based on the information collected for this short-term investigation at the SFWMD S-7 Pump Station, the following conclusions can be formulated:

- The operation of the pump station caused significant mixing of both deep and shallow groundwater and surface water in the headwater side of the pump station. Average SC values of the deep and shallow wells equal the headwater SC levels during pumping activities.
- The DO levels in the headwater were very low, with a mean of 0.59 mg/l (n = 3,284), while the tailwater mean was slightly higher at 0.77 mg/l

(n = 3,023). The lowest DO levels and stratification occurred when the pump was off.

- The United States Geological Survey (USGS) velocity profiles on the headwater side of the pump station indicated a negative velocity away from the pump station during high tailwater elevations. This negative velocity was confirmed by USGS staff in Miami and further confirms the underflow (seepage) from the tailwater side of the pump station to the headwater side when a difference of greater than three feet exists between the two. It should be noted that all pumps are equipped with back flow preventives eliminating any significant siphoning or back flow.
- Pumping elevated the DO levels from 0.25 to 0.75 mg/l in the immediate vicinity of the pump station due to turbulence and aeration effects. The DO levels were slightly higher on the headwater side of the pump station, but pumping influence on DO was observed on both sides.
- The shallow well water levels correlated best with the surface water DO (-0.3645) concentrations. The shallow well water level was inversely related to the DO concentration in the headwater side of the structure. The shallow well water level and the headwater always had a positive net discharge to the canal regardless of pumping activity.
- The deep well water levels seemed to have less influence on DO concentrations. This could be a function of the chronically low levels of surface water or to a limited connection between the headwater elevations and the deep well water levels.
- The SC of the headwater was inversely related to water levels in the shallow well, as was the case with the DO. Higher water levels in the shallow aquifer increased seepage and interflow, but the SC of the groundwater was diluted from rainfall effects.
- The correlation of the deep well SC to the shallow well SC (0.650) was inversely related to the tailwater level (-0.322) and the deep well water level (-0.234). Although these relationships are not direct correlations, they do indicate a role in influencing the results. The correlations were also supported by the upward gradients from the groundwater wells to the surface water.
- Preliminary information indicated that vertical stratification of DO and SC was occurring during cycles when the pumps were not operating at the S-7 Pump Station. During these cycles of no pumping, DO is only found in the top one to two feet of the headwater. This stratification was destroyed during pumping events. This is supported by the headwater SC equaling the SC of the deep well during pumping events, and the headwater conductivity returning slightly higher than the background level of the shallow well after each pumping event.
- During periods when the difference between the headwater and tailwater sides is greater than 3.7 feet, data indicates a significant exchange between the tailwater, groundwater, and the headwater sides of the pump station. This effects the headwater water quality sampling and the overall results.

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ACKNOWLEDGEMENTS

This project could not have been completed without assistance from John Herl, the Chief Operator of the S-7 Pump Station, and his staff. Staff from the Hydrologic Data Processing, Water Quality Monitoring, Electronic Support and Data Acquisition, Everglades, and the Survey and Mapping Departments of the South Florida Water Management District also provided support and assistance to complete this report. A special acknowledgement is made in the memory of Paul Benton, Hydrogeology Division, Water Resources Evaluation, who passed away during this investigation. Also, we would like to acknowledge Kim Jacobs, whose editing and desktop publishing skills have helped bring this document to final publication.

INTRODUCTION

The Everglades Forever Act (EFA) of 1994 set into action a plan for restoring a significant portion of the remaining two million-acre Everglades ecosystem through a program of construction projects, research, and regulation. The EFA called on state and federal agencies to coordinate efforts to conduct comprehensive and innovative studies on issues such as water quality, water quantity, and the hydroperiod of the Everglades ecosystem. Most of this work was the responsibility of the South Florida Water Management (SFWMD), with joint responsibility by the Florida Department of Environmental Protection (FDEP) for more than half of the projects.

Working together, the SFWMD and the FDEP synthesized the requirements of the EFA into seven major elements. One of these elements, Research and Monitoring (RAM), contained three projects focusing on evaluations of water quality and water quality standards. The initial project, RAM-1, Description of Water Quality in the Everglades Protection Area and Tributary Waters, was contracted to Limno-Tech, Inc. (LTI). The objective of RAM-1 was to summarize and characterize available water quality monitoring data and compare these data with Florida's Class III Criteria for Surface Water Quality (Chapter 62-302.530, Florida Administrative Code [F.A.C.]). LTI's report, *Data Analysis in Support of the Everglades Forever Act*, prepared under Contract C-5242, was submitted to the SFWMD on September 15, 1995. This report served as the basis of RAM-3 and -4, Evaluation of Existing Water Quality Standards for the Everglades Protection Area, for which the SFWMD had primary responsibility. It was jointly decided to split apart RAM-3 and -4. The primary objective of RAM-3 was to evaluate, in greater detail, the spatial and temporal nature of the water quality deviations identified in the LTI report, while the primary objective of RAM-4 was to evaluate water quality standards and classification of Everglades Agricultural Area (EAA) canals. Deviations are specific Class III water quality criterion that are exceeded in a sampling event. A RAM–3 secondary objective was to determine if causes of deviations could be identified and, if so, to determine whether the causes were the result of natural processes or human activities.

The RAM-3 analysis of the LTI report revealed that surface water quality deviations of dissolved oxygen (DO) and specific conductance (SC) were occurring throughout the SFWMD, with the majority at SFWMD pump stations. Deviations occurred during both wet and dry seasons, but most commonly in the summer (wet season). Deviations were most pronounced at the S-5A, S-6, and S-7 Pump Stations (**Figure 1**). A number of variables could affect water quality (Belanger and Heck, 1994) and cause these deviations, including groundwater inflow and outflow, surface water velocity profiles, groundwater flow beneath the pump station, and seepage from the headwater and tailwater side. The pump operating schedule, pump capacity, and pump revolutions per minute (rpm) can also influence water quality near a pump station.

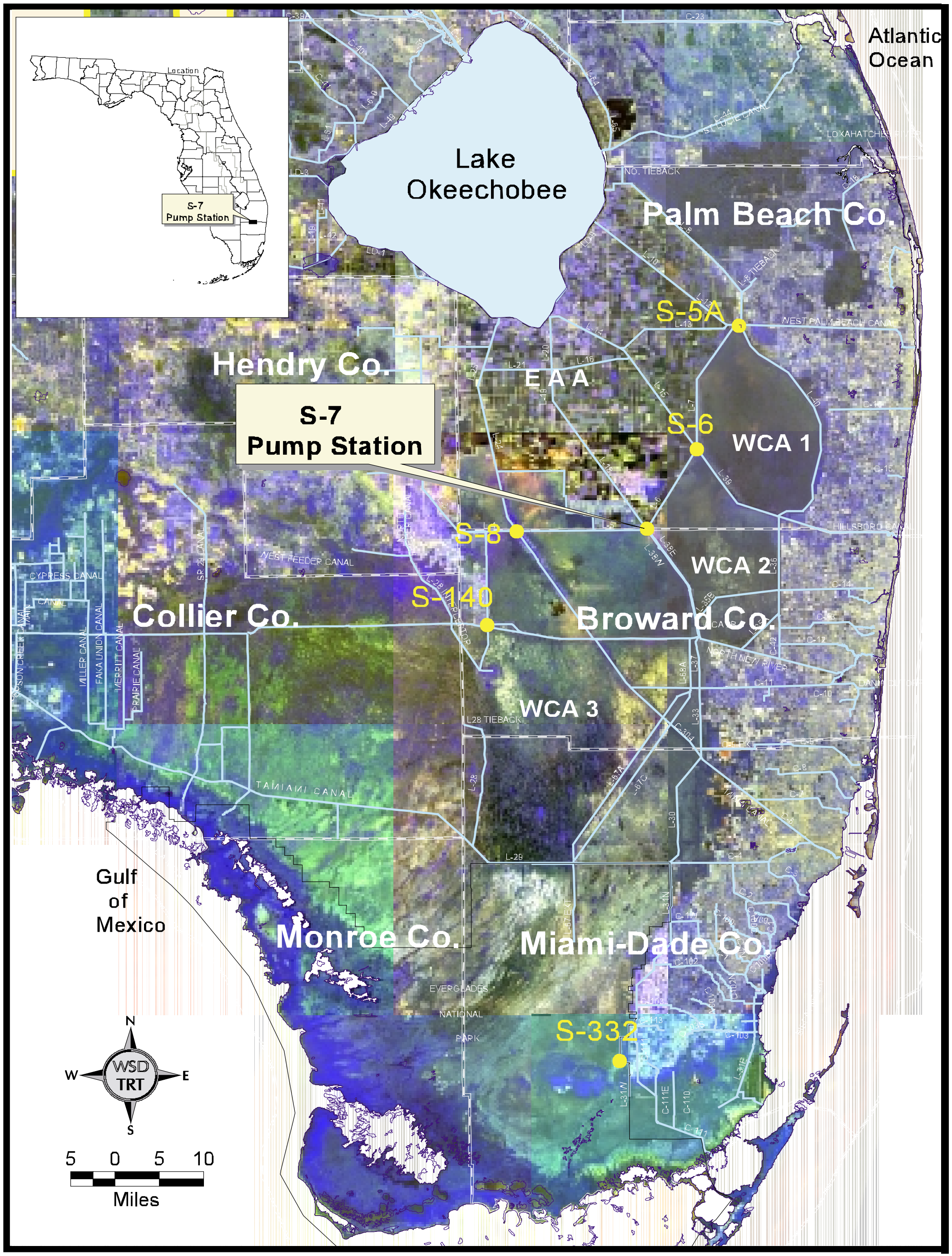


Figure 1. S-5A, S-6, S-7, S-8, S-140, and S-332 Pump Stations

Groundwater generally has lower DO and higher SC levels than surface water; seasonal changes in rainfall can cause variations in both aquifer and canal water levels. The changing levels will affect the hydraulic gradient between surface water and groundwater, which can alter the seepage rates. During the dry season (November through May), canal water levels are low and the difference between headwater and tailwater elevations is generally at a minimum. In this case, the groundwater provides significant inflow through the banks of the canals. This could lead to low DO and elevated SC levels in the surface water in both the headwater and the tailwater.

During the wet season (June through October), the canal water levels are higher, pump station headwater and tailwater differences are the greatest, and seepage through the canal banks is minimal. Under these conditions, seepage rates are driven by the increased difference between the headwater and tailwater, and seepage under and around the ends of the structure would occur at the highest rate. It is thought that the pressure associated with the larger elevation differential would cause a downward displacement of the tailwater water into the aquifer and force groundwater under the pump station to the lower head side. This could lead to decreased DO and elevated SC levels in the surface water in the headwaters.

PURPOSE

Before receiving the RAM-1 report, which indicated potential interactions occurring at pump stations, the SFWMD had never evaluated the effects of pump stations on the surface-groundwater interactions. Therefore, the SFWMD and the FDEP agreed that a short-term surface water-groundwater investigation should be conducted at a pump station. The LTI data and the existing infrastructure were evaluated to determine the most appropriate site for the study. The S-7 Pump Station was selected based on the LTI data and on the availability of existing headwater and tailwater recording devices, a rainfall gage, nearby monitor wells, and the United States Geological Survey (USGS)-maintained ultrasonic velocity meter (UVM). Data and results from this investigation would then be used to guide future longer-term investigations and S-7 operations, and would provide recommendations for interpreting water quality deviations.

The objectives of the field investigation were as follows:

- Assess the effect of pumping activity on surface and groundwater levels
- Estimate the interaction between the surface water and groundwater
- Determine if the pump station activity degrades or improves the surface water and/or groundwater quality, in terms of DO and SC
- If it was found that pump station activity caused water quality degradation, determine if the degradation is abatable through a change in pump station activity
- Provide recommendations for the RAM-3 report on water quality deviations and their relationship to existing state water quality standards

- Provide recommendations and guidance for future investigations at additional pump stations

BACKGROUND

Review of the surface water quality data from the LTI (1995) report indicated that a significant number of surface water quality deviations at the SFWMD's pump stations occurred during both the wet and dry seasons. It was hypothesized that interactions among water levels, water quality, and pumping rate could result in the observed deviations. Typical variables that may affect pump station water quality include surface water inflow and outflow, pump drive engine rpm, pump operating schedules and capacities, groundwater inflow and outflow, seepage from the headwater and tailwater sides as a function of stage, and surface water velocity profiles (**Figure 2**).

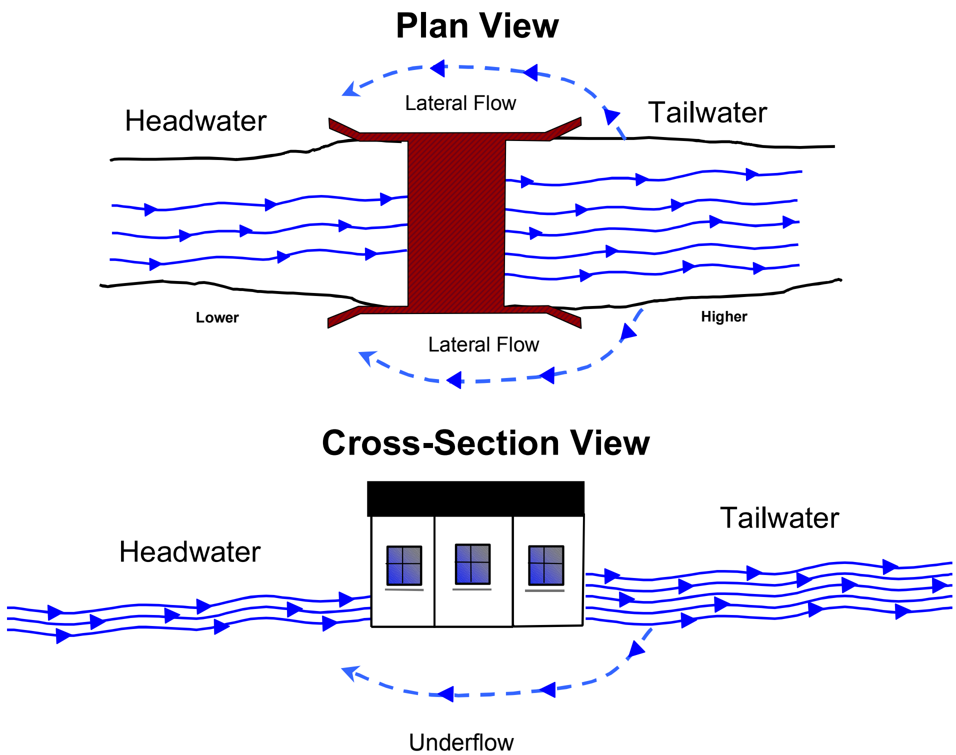


Figure 2. Idealized Pump Station Cross-Section

It is known that seasonal changes in rainfall cause variations in aquifer water levels. In the vicinity of pump stations, these seasonal aquifer water level variations can result in DO and SC criteria deviations. During the dry season, when canal water levels are low, groundwater provides significant inflow to the canals, lowering DO concentrations and increasing SC readings. Although tailwater elevations exceed headwater elevations at pump stations throughout the year, the difference between headwater and tailwater levels is usually at a minimum during the dry season. In the wet season, canal water levels are higher, normal groundwater inflow through canal banks is minimal, and pump station headwater and tailwater differences are the greatest. Under wet season conditions, seepage under and around the ends of the structure would occur at the highest rate when the tailwater-headwater differential is the greatest. It was surmised that the pressure associated with the larger differential would cause a downward displacement of the tailwater water column into the aquifer and force groundwater under the pump station to the headwater side. During these conditions, groundwater flow into the headwater of the canal would be at a maximum and would be characterized by high SC and low DO.

Since the SFWMD had never before evaluated the effects on water quality as a result of pump station operations, it was decided by the SFWMD and the FDEP that a short-term surface water-groundwater investigation was needed at a selected pump station. Data and results from this investigation would then be used to guide future longer-term investigations at S-7 and provide recommendations for interpreting water quality deviations.

Before selection of the pump station to be used in the study, historical water quality data were analyzed for DO and SC deviations during the wet and dry seasons. Using the historical information, the investigators were able to confirm when deviations for these parameters had occurred at particular pump stations. These parameters became key variables in the selection of the proposed field investigation site.

HISTORICAL REVIEW OF DISSOLVED OXYGEN AND SPECIFIC CONDUCTANCE

Historical review (1979 to 1993) of deviations from the state criteria for DO (5.0 milligrams per liter [mg/l]) and SC (1,275 microseconds/centimeter [µS/cm]) at key pump stations (S-5A, S-6, S-7, S-8, S-140, and S-332) (**Figure 1**) indicated that deviations occurred both in the dry (November to April) and wet seasons (May to October). Seasonal differences in DO deviations are summarized in **Table 1**. Data histograms of DO by season are provided in **Appendix A**, **Figures A-1** through **A-13**. These data show that DO deviations were found at all pump stations. A greater number of deviations occurred at these pump stations in the wet season (average = 133.3) than in the dry season (average = 80.8). In addition, distributions were skewed to the lower DO concentrations during the wet season.

Table 1. Dissolved Oxygen Deviations at Selected Pump Stations

Pump Station	Deviant Wet Season Samples		Total Number of Wet Season Samples	Deviant Dry Season Samples		Total Number of Dry Season Samples
	Number	Percent		Number	Percent	
S-5A	116	85.9	135	68	53.9	126
S-6	155	90.1	172	112	74.2	151
S-7	134	82.7	162	95	55.6	171
S-8	131	74.4	176	72	41.1	175
S-140	143	79.4	180	60	37.5	160
S-332	121	84.6	143	78	56.5	138

Seasonal differences in SC deviations are summarized in **Table 2**. Specific conductivity data histograms by season are provided in **Appendix A**, **Figures A-14** through **A-24**. These data indicate that SC deviations are most frequent at S-6, in both the wet and dry seasons. In addition, the greater number of deviations occurred at S-6 in the wet season, whereas the dry season produced the greater number of deviations at S-5A and S-7.

Table 2. Specific Conductivity Deviations for Selected Pump Stations

Pump Station	Deviant Wet Season Samples		Total Number of Wet Season Samples	Deviant Dry Season Samples		Total Number of Dry Season Samples
	Number	Percent		Number	Percent	
S-5A	26	19.8	131	38	31.7	120
S-6	96	63.6	151	64	42.4	151
S-7	22	13.5	163	42	24.6	171
S-8	1	0.6	175	1	0.6	172
S-140	0	0	178	0	0	160
S-332	0	0	137	0	0	142

CRITERIA FOR SELECTING S-7 PUMP STATION

The S-7 investigation began by interviewing staff from the Operations and Maintenance Control Room, various pump station staff, and personnel from the Hydrogeology Division's Ambient Groundwater Quality Monitoring Program. In addition, site visits were conducted to all the pump stations located between the EAA and the Everglades Protection Area. At pump stations S-5A, S-6, S-7, S-8, and S-140, groundwater monitoring wells previously installed under the FDEP's and the SFWMD's Ambient Groundwater Quality Monitoring Programs were examined for location and distance to the structure. After reviewing all available information, the S-7 site was selected for this investigation based on the following key factors:

- The site already had monitor wells in place on the upstream (headwater) side of the pump station. At other structures, wells were too far away (S-5A) or were downstream (S-140) of the structure.
- The site was within a one-day travel time (round trip) of the SFWMD's headquarters. This allowed for a full day's work without an overnight stay.
- The SFWMD currently samples water quality at the headwater of S-7. More than 20 years of water quality data are available for this site.
- More than 20 years of historical flow data and engine rpm data are available for S-7.
- The USGS was monitoring flow at the site with UVM underwater velocity profiling equipment on the headwater side of the pump station.
- The site had elevation controls established on the headwater and tailwater sides of the structure.
- The site was located between the EAA and Everglades Protection Area.

SITE DESCRIPTION AND BACKGROUND

Location

The S-7 Pump Station (**Figure 3**) is located on State Road 27 at the Palm Beach-Broward County border **(Figure 4**). The pump station has three horizontal pumps, rated at 830 cfs each, with a total pumping rate of 2,490 cfs, and one spillway. The maximum operating head difference between the headwater and tailwater elevations is set at 5.3 feet. The station bridges the North New River Canal and pumps from the EAA into Water Conservation Area 2A (WCA-2A). A detailed site map of the study area is shown in **Figure 5**.

Figure 3. Aerial Photo of S-7 Pump Station from the Southwest

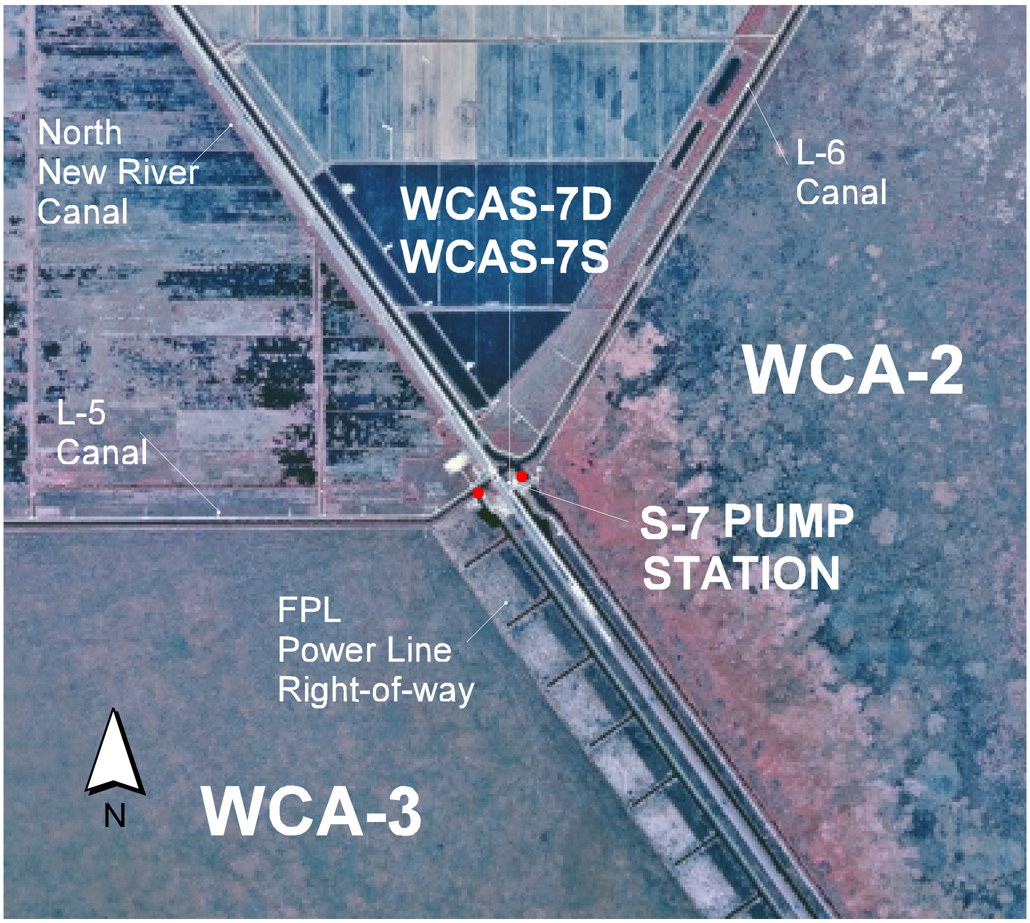


Figure 4. S-7 Site Location on State Road 27, Palm Beach-Broward County Line

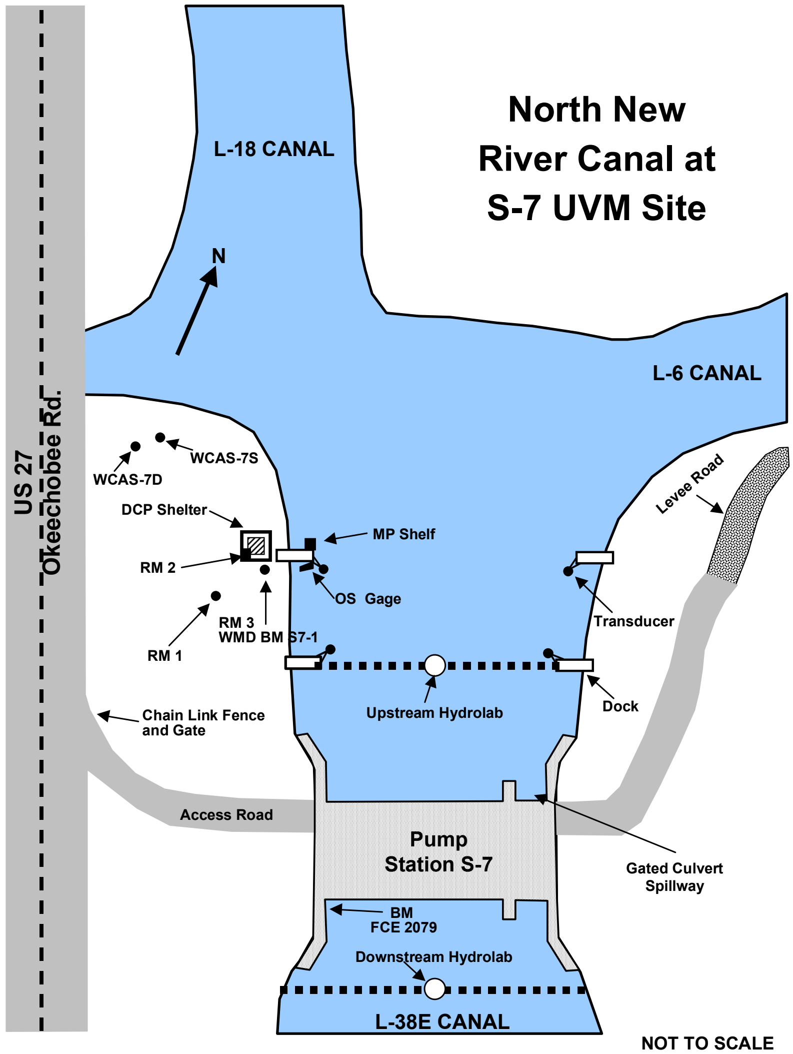


Figure 5. Site Map for S-7 Pump Station Investigation

GEOLOGY

The original geology, investigated for the construction of the pump station foundation by the United States Army Corps of Engineers (USACE*),* is shown in **Figures 6** and **7** (modified from USACE, 1955). A plan view site map of the cross-sections are shown in **Appendix B**, **Figure B-1**. Groundwater flow paths are shown in **Appendix B**, **Figures B-2** and **B-3**. A detailed lithologic description for the deep well (WCAS-7D) is provided in **Appendix B**, **Figure B-4**.

The site is underlain by alternating layers of sand, limestone, shell, and freshwater marl. Several layers of dense, highly-cemented limestone are present and relatively continuous throughout the site. These alternating layers might serve as “conduits” to transport water through the aquifer based on hydraulic gradients within the different layers.

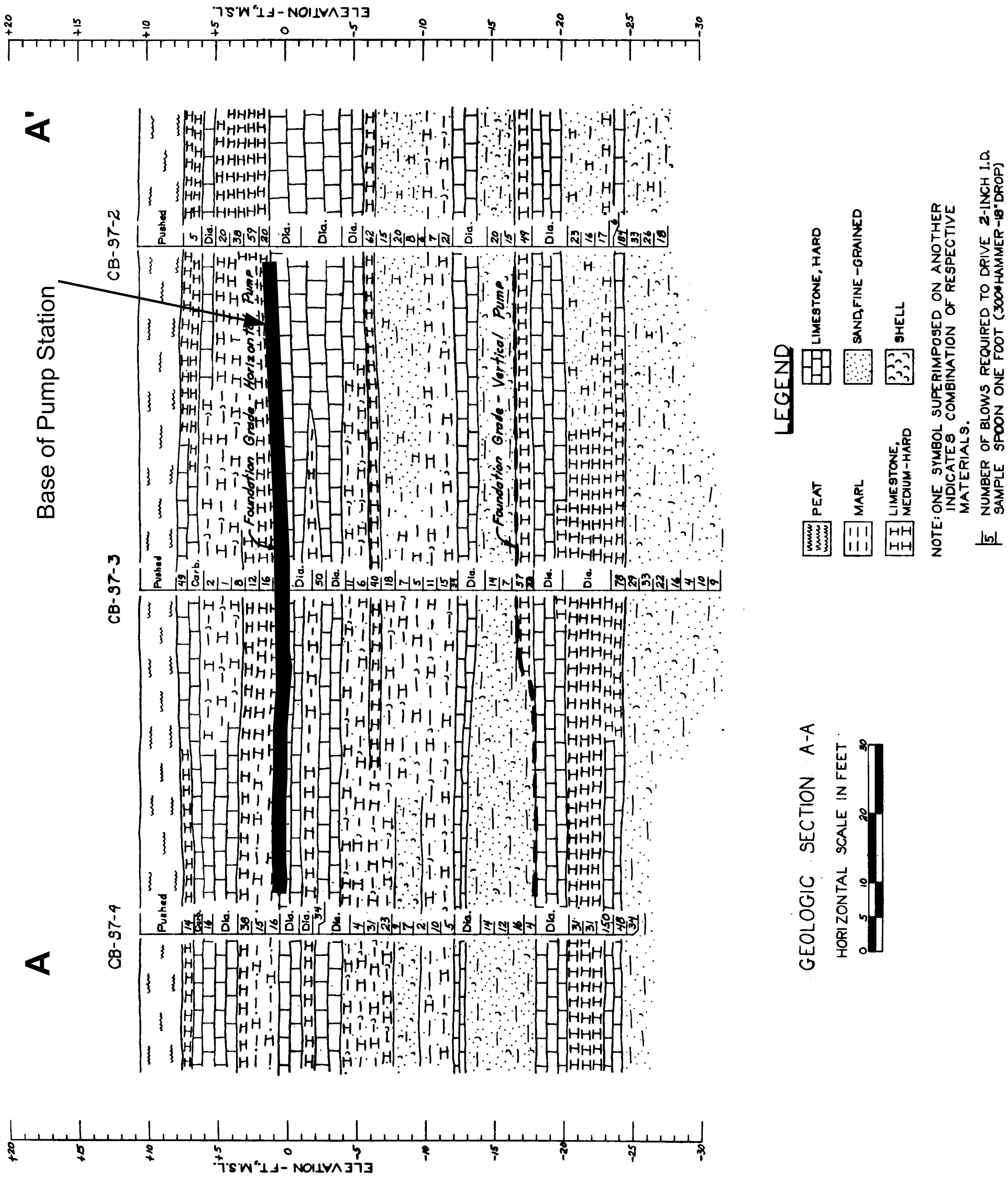


Figure 6. Base of Pump Station Northeast-Southwest, Geologic Section A-A' (Dia. = diameter that borehole was cored)

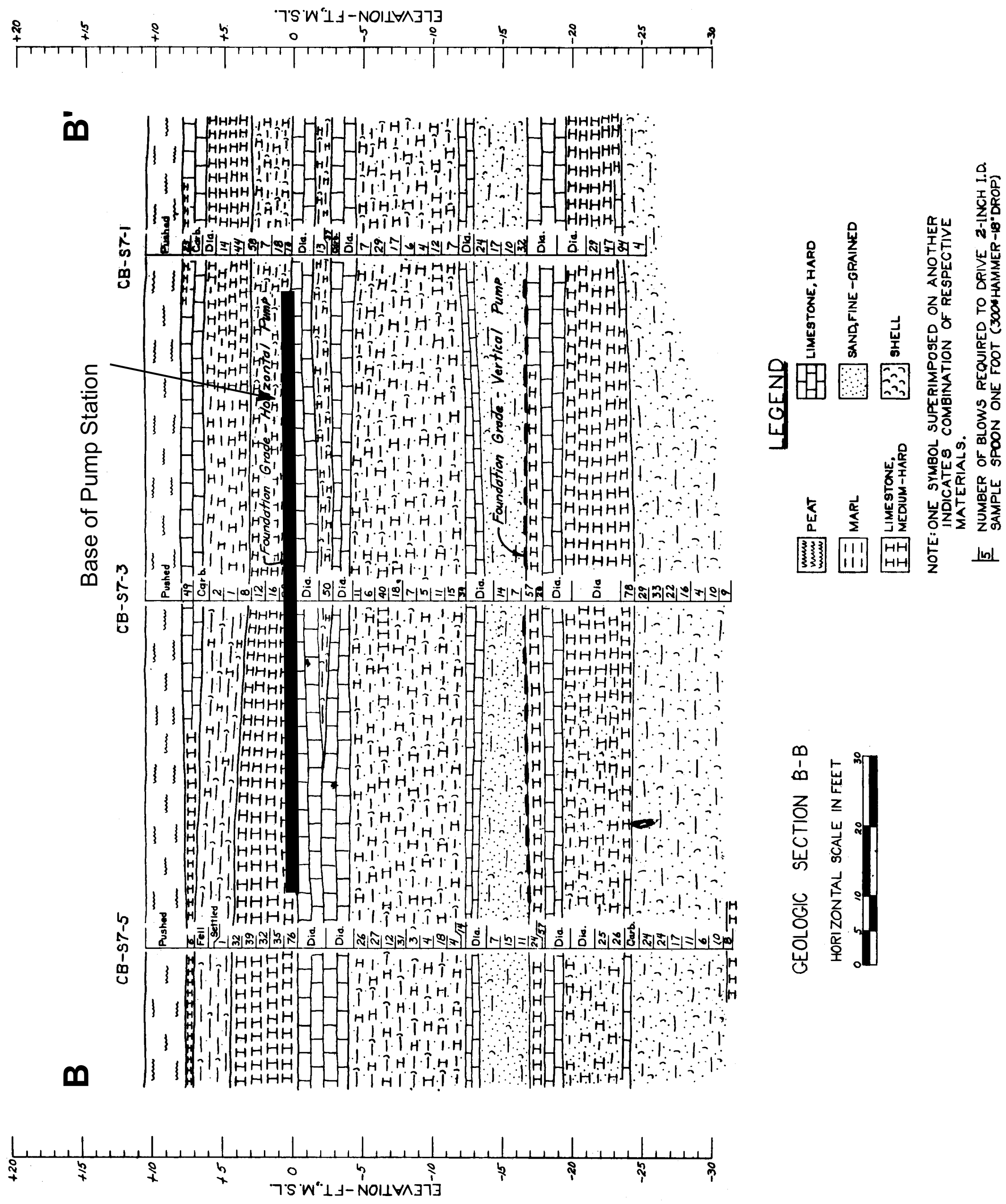


Figure 7. Base of Pump Station Northwest-Southeast, Geologic Section B-B' (Dia. = diameter that borehole was cored)

METHODS

Equipment Setup and Data Collection

The authorization to proceed with this investigation was received from the FDEP in August 1995, and preparation for the field work began immediately. The field data collection for this project occurred from September 13 to November 7, 1995.

Information obtained from the RAM-1 report (LTI, 1995) indicated that the largest number of deviations at S-7 were for DO and SC. To assess the S-7 operations, the following variables were monitored: headwater and tailwater stage, groundwater level, temperature, surface water pH, conductivity, temperature, DO, and total dissolved solids (TDS) in both the headwater and tailwater segments. The investigation was an assessment of the relationship of water quality to water levels as a result of pumping and nonpayment activity. During the field work phase, the pump station used all three pumps on several occasions with extended periods of both pumping and no pumping.

Pressure transducers were installed in monitor wells WCAS-7S (shallow) and WCAS-7D (deep) (**Figures 4** and **5**). Insitu™ water quality probes measuring conductivity and temperature were placed near the bottom of the screen interval of both monitor wells. Measurements were taken and recorded every 15 minutes. Since the groundwater quality conductivity probes were not temperature-corrected, a temperature correction was applied to convert conductivity data to SC values after downloading to a personal computer.

Hydrolab™ water quality sensors were installed on the headwater and the tailwater sides of the structure on September 23, 1995 (**Figures 2** and **8**). Initially, the sensors were installed within small tire tubes to assist in maintaining flotation. The sensors were 1.25 feet below the water surface. Water depth in the center of the channel is approximately 15 feet in the headwater and 13 feet in the tailwater. The tire tubes were anchored to permanent structures with nylon rope. The equipment was placed midway between the banks of the canal (**Figure 8**), 118.5 feet upstream from the pump station intake and 49.2 feet downstream of the discharge. After the tires were attacked several times by alligators, the tire tubes were eliminated, and the sensors were secured directly to each canal bank using 1/4-inch nylon rope. The sensors were installed with stirrers activated with the appropriate warm-up times. The logging frequency was set at 15 minutes for all parameters.

The surface water pressure transducers were installed in the stillwell at the northernmost UVM site in the headwater and against the headwall on the west side of the tailwater structure (**Figures 2** and **5**). **Table 3** summarizes the data collection locations and instruments used.

Weekly site visits were made to manually measure groundwater and surface water levels. This allowed the investigators to cross-check water level data, which served as a calibration point for the final analysis and data presentation. Each week, the electronic

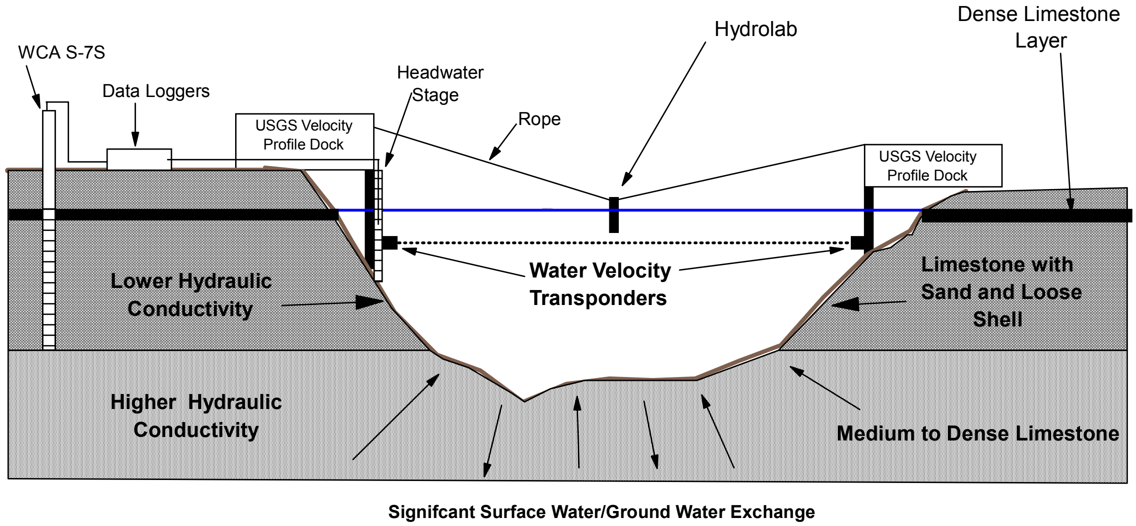


Figure 8. Scaled A-A' Cross-Section of Headwater Upstream at S-7

Table 3. Water Quality and Water Level Parameters Collected at S-7 Pump Station by Various Data Loggers

Parameter	Headwater Stage	Tailwater Stage	S-7 Deep	S-7 Shallow
Water Level (Relative Change)	In-Situ	In-Situ	In-Situ	In-Situ
Location of Reading	North Stillwell	South Stillwell	Groundwater Well	Groundwater Well
SC	Hydrolabs	Hydrolabs	In-Situ [a]	In-Situ[a]
Temperature	Hydrolabs	Hydrolabs	In-Situ	In-Situ

a. Conductivity only

data from the headwater and tailwater Hydrolab™ data loggers were downloaded. The pH, SC, and DO probes of the Hydrolab™ sensors were recalibrated, the batteries were changed, and the exterior was cleaned. The data were downloaded to a personal computer. Generally, sensor batteries only lasted for a week. When the batteries still had ample voltage to power the probes, the calibration procedure was completed before downloading the previous week's data. Low voltage readings were a common cause of automatic shutdown of the sensor's probes during the investigation.

Site Surveying

SFWMD staff surveyed the measuring points for the top of the monitor well casings (**Table 4**), ground surface elevations (**Table 4**), location of S-7 shallow and deep monitor wells (**Table 5**), and the cross-sections of the headwater and tailwater segments (**Table 6**). Spatial locations and distances were calculated for establishing gradients.

Table 4. Pump Station S-7 Monitor Well As-Built Construction Data

Well	Land Surface[a] (feet NGVD)[b]	Measuring Point (feet NGVD)[a]	Cased Depth (ft)[c]	Total Depth (ft)[c]	Screen Length (feet)[c]	Screen Interval Relative to feet NGVD	
						Top of Screen Interval	Bottom of Screen Interval
S-7 Deep[d]	15	16.78	85.8	95.8	10	-69.02	-79.02
S-7 Shallow[3]	15	16.77	5.9	15.9	10	+10.87	+0.80

a. Wells were surveyed by the SFWMD.
b. NGVD = National Geodetic Vertical Datum, 1929.
c. Well construction information supplied by the SFWMD.
d. Wells installed by the SFWMD in March 1993.

Table 5. Florida State Planar Coordinates for the Groundwater Monitor Wells and the Center Point of the S-7 Pump Station

Location	Easting	Northing
WCA2S-7D [a]	651,299.594	727,917.278
WCAS-7S [a]	651,299.231	727,914.651
S-7 Pump Station[b]	651,633. 000	727,730.000
Distance between center of pump station and well WCAS-7S (ft)	333 feet (West of pump station)	184 feet (North of pump station)

a. Wells were surveyed using a differential corrected global positioning satellite by the SFWMD on March 1, 1996.
b. As-built survey for S-7 Pump Station was produced by the USACE (1955). The coordinates were provided by the SFWMD on March 1, 1996.

Table 6. Cross-Sectional Area of S-7 Pump Station Headwater and Tailwater

Cross-Section Location	Distance from Pump Station (feet)	Date of Surveying	Water Level at Time Of Surveying (feet NGVD)	Cross-Sectional Area (square feet)
Northern Cross-Section (Headwater)	223	November 11, 1995	10.82	1,614.90
Southern Cross-Section (Tailwater)	149	November 11, 1995	13.58	1,611.97

Statistical Analysis

It was hypothesized that there were significant correlations between water levels, water quality, pump engine speed, and barometric pressure. Correlation analysis (Spearman, Kendall) was used on the respective parameters to test this hypothesis. The correlation analyses also included using pump engine on (rpm > 0.0) and pump engine off (rpm = 0.0) conditions, for the total period of the investigation. Parameters that significantly correlated at the $\alpha = 0.05$ level were investigated graphically.

The study was divided into two periods for interpretation. The first period was September 14, 1995 to October 10, 1995. The second period was from October 11, 1995 to November 7, 1995. The site investigation was completed on November 7, 1995.

RESULTS

The water level and water quality results of the S-7 structure are presented and discussed by period.

Water Levels

Water Level Data for Period 1

Water levels during Period 1, September 14 to October 10, 1995, were declining at the pump station. The hydrographs indicated a downward trend in surface water and groundwater levels (**Appendix C**, **Figure C-1**). However, several large tropical storms had recently altered weather patterns on the Florida peninsula. Hurricane Opal approached on October 3 and 4, 1995, and passed within several hundred miles of the west coast of Florida. Hurricane feeder bands dropped heavy rainfall in the study area and water levels rose. The downward trend in water levels was also periodically reversed by pumping activity. During Hurricane Opal, pumping activity raised the tailwater 1.2 feet. The wet season water levels were normal for this time of year. The range for the headwater elevations was from 9.76 to 12.58 feet with a mean of 10.56 feet (n = 2,623). The tailwater elevations ranged from 13.46 to 15.28 feet with a mean of 14.27 feet (n = 2,623). The shallow monitor well water level ranged from 10.36 to 12.46 feet with a mean of 10.99 feet (n = 2,623), while the deep well water level ranged from 9.54 to 11.36 feet with a mean of 10.34 feet (n = 2,623). The data are summarized in **Table 10**. All elevations are referenced to the National Geodetic Vertical Datum of 1929 (NGVD).

Water Level Data for Period 2

Water levels during Period 2, October 11 to November 7, 1995, continued on a downward trend until October 14, 1995, when extensive pumping occurred, raising the tailwater to above 14.0 feet (**Appendix C**, **Figure C-1**). Water levels rose slightly (0.25 feet) in the headwater and shallow well. The tailwater was elevated 1.5 feet after the pumping activity began and slowly declined after the pumping activity stopped. The deep well water level rose above the headwater and shallow well groundwater level and stayed at this level until the end of the study. The headwater level and shallow groundwater level stayed within a similar window (9.5 to 11.5 feet) of water elevations as in Period 1. The range for the headwater elevations was from 9.40 to 11.27 feet with a mean of 10.50 feet (n = 2,622). The tailwater elevations ranged from 13.45 to 15.27 feet with a mean of 14.56 feet (n = 2,634). The shallow well water level ranged from 10.23 to 11.91 feet with a mean of 11.01 feet, while the deep well water level ranged from 9.53 to 12.03 feet with a mean of 11.08 feet (n = 2,622). The data are summarized in **Table 10**.

Water Quality Results

Water quality samples were collected from both wells, the headwater, and the tailwater at the S-7 site. **Table 7** presents the laboratory results for samples collected on September 12, 1995. Prior to this sampling event, pumps had been running for two days. **Table 8** presents the laboratory data for samples collected on November 7, 1995. Prior to this sampling event the pumps had not run for three days. The nutrient data are presented as background information and not discussed in the text.

Table 7. Water Quality Samples Taken at the S-7 Pump Station during the Test Setup of Data Loggers on September 12, 1995

Parameter	S-7 Deep Time: 10:25	S-7 Shallow Time: 12:50	Headwater Time: 13:22	Tailwater Time: 13:53
Temperature (0C)	24.7	26.1	26.7	26.6
pH	6.8	6.7	6.8	6.7
SC (µS/cm)	1,429	1,024	883	903
DO (mg/l)	No Reading	No Reading	1.9	1.9
Redox (millivolt)	-40.0	-8.0	142.0	19
Water Level in feet from TOC[a]	-5.8	-6.0	No Reading	No Reading
Water Level in feet (mean sea level [MSL])	11.0	10.8	10.4[b]	15.2[b]
Calcium (Ca) (mg/l)	78.4	130.1	102.8	109.9
Magnesium (Mg) (mg/l)	60.6	32.7	28.3	31.7
Potassium (K) (mg/l)	8.9	6.5	5.9	6.5
Sodium (Na) (mg/l)	144.7	44.6	44.6	47.5
Total Aluminum (Al) (mg/l)	75.7	417.9	111.6	136.5
Total Iron (Fe) (mg/l)	39.2	463.0	124.0	136.0
Chloride (Cl) (mg/l)	158.4	59.1	67.2	72.9
Nitrate-Nitrite (NO_X) (mg/l)	0.02	0.02	0.34	0.38
Total Kjeldahl Nitrogen (TKN) (mg/l)	1.3	3.7	2.0	2.2
Orthophosphate (OPO_4) (mg/l)	< 0.004	0.004	0.04	0.04
Total Phosphate (TPO_4) (mg/l)	0.02	0.02	0.07	0.09
Sulfate (SO_4) (mg/l)	21.1	< 2.0	35.2	39.7

a. TOC = Top of casing; the measuring point from which all water level measurements are made
b. No surface water elevations were taken during water quality sampling. Water levels from in-situ data loggers from the headwater and tailwater readings at 16:25 on September 13, 1995.

Table 8. Water Quality Samples Taken at the S-7 Pump Station at the End of the Investigation on November 7, 1995

Parameter	S-7 Deep Time: 12:30	S-7 Shallow Time: 11:30	Headwater Time: 13:00	Tailwater Time: 13:30
Temperature (^oC)	24.2	26.1	25.9	27.3
pH	6.8	6.7	6.8	7.0
SC (μS/cm)	1,436	1,049	627	828
DO (mg/l)	No Reading	No Reading	2.2	5.3
Redox (millivolt)	-31.0	0.0	2.2	2.2
Water level in feet from TOC[a]	-5.4	-5.5	No Reading	No Reading
Water level in feet (mean sea level [MSL])	11.4	11.3	11.3[b]	11.8[b]
Ca (mg/l)	78.4	126.9	78.3	71.9
Mg (mg/l)	59.8	34.6	15.6	24.3
K (mg/l)	8.3	5.1	2.6	6.4
Na (mg/l)	139.6	50.6	29.1	60.6
Total Al (Tg/L)	455.7	155.0	15.6	13.4
Total Fe (Tg/L)	200.7	285.9	124.5	121.7
Chloride (mg/l)	162.2	76.8	45.9	94.0
NO_X (mg/l)	0.01	0.27	0.05	0.02
TKN (mg/l)	1.6	4.0	1.2	1.9
TPO_4 (mg/l)	0.25	0.35	0.02	0.06
OPO_4 (mg/l)	< 0.004	< 0.004	< 0.004	0.007
SO_4 (mg/l)	19.9	< 2.0	13.4	50.3

a. TOC = Top of casing; the measuring point from which all water level measurements are made
b. No surface water elevations were taken during water quality sampling. Water levels are from in-situ data loggers from the headwater and tailwater readings at 08:00 on November 7, 1995.

Summary statistics for all field data are provided for Period 1 (**Table 9**), Period 2 (**Table 10**), and Periods 1 and 2 (**Table 11**). Graphical outputs have been grouped by parameter (i.e., water levels, DO, SC) for each period to allow for the visual comparison between periods (**Appendix C**, **Figures C-1** through **C-9**). **Appendix C** provides graphs of water quality data grouped by the two study periods. Period 1 covers September 14 to October 10, 1995, while Period 2 covers October 11 to November 7, 1995. Each pair of figures shows similar parameters to allow the comparison of the two time periods. The following paragraphs summarize the field data collected in the study.

Table 9. Summary Table for Parameters for Period 1 (September 14 to October 10, 1995)

Variable	N	Mean	Std Dev	Median	Minimum	Maximum
H_STG	2623	10.5618	0.4587	10.4720	9.7660	12.5850
S7DEEP	2623	10.3486	0.4921	10.2860	9.5470	11.3650
S7SHALL	2623	10.9946	0.3479	10.9260	10.3660	12.4620
S7D_TEMP	2623	23.9164	0.009103	23.9150	23.8880	23.9810
S7S_TEMP	2623	25.9136	0.2329	25.8130	25.6210	26.6170
T_STG	2623	14.2710	0.4929	14.2060	13.4670	15.2850
HEADTEMP	1423	27.5672	0.3787	27.5200	26.7600	29.0000
HEADPH	1423	7.1131	0.2171	7.2800	6.7700	7.3500
HEADCOND	1423	855.6774	138.3173	857.0000	629.0000	1144
HEADDO	1423	0.5336	0.4469	0.4500	0.0400	1.7100
TAILTEMP	1418	27.9379	0.9660	27.6900	26.7600	32.2000
TAILPH	1418	7.0980	0.2115	7.0900	6.6800	7.6800
TAILCOND	1415	921.3095	101.8477	929.0000	655.0000	1125
TAILDO	1415	0.6994	0.4667	0.6700	0.0400	2.5200
ENG_RPM	2623	369.6493	505.6311	0	0	2040
BAROM	2623	29.8867	0.0783	29.8800	29.7020	30.0940
HDDIFF	2623	0.2132	0.7225	0.2220	-1.3260	2.9430
DSDIFF	2623	-0.6459	0.6370	-0.6580	-2.8200	0.7310
SHDIFF	2623	0.4337	0.1142	0.4520	-0.0700	0.6810
TDDIFF	2623	3.2764	0.6457	3.2620	1.1000	4.6510
TSDIFF	2623	3.2764	0.6457	3.2620	1.1000	4.6510
THDIFF	2623	3.7092	0.7320	3.6960	0.9770	5.2460
DSGRAD	2623	-0.009251	0.009123	-0.009420	-0.0404	0.0105
SHGRAD	2623	0.004328	0.001177	0.004520	-0.001230	0.006810
HDGRAD	2623	0.003320	0.0113	0.003458	-0.0207	0.0458
VEL1	2623	0.3125	0.3961	0.0175	-0.2600	1.8300
VEL2	2622	0.3174	0.3942	0.0515	-0.0700	1.9300
VELAVG	2622	0.3149	0.3941	0.0296	-0.1169	1.8000
SCONDDP	2623	1034	59.7935	1027	892.9299	1945
SCONDSH	2623	647.0595	102.1776	652.6001	464.4811	1338

Table 10. Summary Table for Parameters for Period 2 (October 11 to November 7, 1995)

Variable	N	Mean	Std Dev	Median	Minimum	Maximum
H_STG	2622	10.5032	0.4910	10.5000	9.4080	11.7270
S7DEEP	2622	11.0817	0.6632	11.2710	9.5370	12.0320
S7SHALL	2622	11.0136	0.3424	10.9740	10.2310	11.9110
S7D_TEMP	2622	23.9144	0.006561	23.9150	23.8930	23.9420
S7S_TEMP	2622	26.1735	0.4043	25.9720	25.7090	26.9950
T_STG	2633	14.5682	0.4396	14.6410	13.4570	15.2750
HEADTEMP	1861	25.9517	0.8107	25.6500	24.6100	29.2400
HEADPH	1861	7.1446	0.1363	7.1200	6.9700	8.9000
HEADCOND	1859	843.4422	128.5043	825.0000	603.0000	1240
HEADDO	1861	0.6328	0.4725	0.6100	0.0400	1.8400
TAILTEMP	1608	25.9598	0.9584	25.6500	24.2400	29.4000
TAILPH	1608	7.0681	0.0531	7.0500	6.9800	7.2800
TAILCOND	1607	856.2054	131.8293	849.0000	537.0000	1098
TAILDO	1608	0.8327	0.4999	0.8450	0.0700	2.1200
ENG_RPM	2633	622.2902	709.6251	500.0000	0	2040
BAROM	2633	29.9587	0.0943	29.9490	29.7280	30.1510
HDDIFF	2633	-0.5761	0.6912	-0.7990	-1.7590	2.1140
DSDIFF	2633	0.0678	0.6155	0.3090	-2.2980	0.9450
SHDIFF	2633	0.5083	0.1706	0.4740	0	0.8350
TDDIFF	2622	3.3817	0.6641	3.2570	1.6410	4.8270
TSDIFF	2630	3.5576	0.6235	3.5660	1.6410	4.8270
THDIFF	2622	4.0646	0.7731	4.0180	1.8250	5.6600
DSGRAD	2633	0.000972	0.008815	0.004426	-0.0329	0.0135
SHGRAD	2633	0.005083	0.001706	0.004740	0	0.008350
HDGRAD	2633	-0.008974	0.0108	-0.0125	-0.0274	0.0329
VEL1	2584	0.5393	0.5957	0.4850	-0.1800	1.9700
VEL2	2584	0.5460	0.5842	0.5150	-0.1500	1.9400
VELAVG	2631	0.5329	0.5876	0.4550	-0.1000	1.8650
SCONDDP	2622	1037	43.5005	1019	906.8495	1260
SCONDSH	2622	648.0311	100.8241	665.8113	471.3262	986.8732

Table 11. Summary Table for Parameters for Entire Study Period (September 14 to November 7, 1995)

Variable	N	Mean	Std Dev	Median	Minimum	Maximum
H_STG	5245	10.5325	0.4760	10.4820	9.4080	12.5850
S7DEEP	5245	10.7151	0.6894	10.8350	9.5370	12.0320
S7SHALL	5245	11.0041	0.3453	10.9450	10.2310	12.4620
S7D_TEMP	5245	23.9154	0.007998	23.9150	23.8880	23.9810
S7S_TEMP	5245	26.0435	0.3546	25.9060	25.6210	26.9950
T_STG	5256	14.4199	0.4900	14.5750	13.4570	15.2850
HEADTEMP	3284	26.6518	1.0371	27.0300	24.6100	29.2400
HEADPH	3284	7.1309	0.1766	7.1300	6.7700	8.9000
HEADCOND	3282	848.7471	132.9658	831.0000	603.0000	1240
HEADDO	3284	0.5898	0.4641	0.5100	0.0400	1.8400
TAILTEMP	3026	26.8867	1.3783	27.2200	24.2400	32.2000
TAILPH	3026	7.0821	0.1506	7.0600	6.6800	7.6800
TAILCOND	3022	886.6893	123.0842	889.0000	537.0000	1125
TAILDO	3023	0.7703	0.4891	0.7500	0.0400	2.5200
ENG_RPM	5256	496.2100	629.0777	0	0	2040
BAROM	5256	29.9228	0.0939	29.9150	29.7020	30.1510
HDDIFF	5256	-0.1822	0.8097	-0.3355	-1.7590	2.9430
DSDIFF	5256	-0.2884	0.7208	-0.1410	-2.8200	0.9450
SHDIFF	5256	0.4711	0.1499	0.4600	-0.0700	0.8350
TDDIFF	5245	3.3291	0.6570	3.2580	1.1000	4.8270
TSDIFF	5253	3.4172	0.6500	3.3790	1.1000	4.8270
THDIFF	5245	3.8868	0.7734	3.8290	0.9770	5.6600
DSGRAD	5256	-0.004130	0.0103	-0.002020	-0.0404	0.0135
SHGRAD	5256	0.004706	0.001514	0.004600	-0.001230	0.008350
HDGRAD	5256	-0.002838	0.0126	-0.005225	-0.0274	0.0458
VEL1	5207	0.4250	0.5176	0.0349	-0.2600	1.9700
VEL2	5206	0.4309	0.5106	0.0800	-0.1500	1.9400
VELAVG	5253	0.4241	0.5122	0.0439	-0.1169	1.8650
SCONDDP	5245	1035	52.3021	1022	892.9299	1945
SCONDSH	5245	647.5452	101.4947	659.7415	464.4811	1338

Table 12. Legend for Summary Tables

Variable	Definition	Units
H_STG	Headwater Stage	feet NGVD (1929)
S7DEEP	Deep Well Water Elevation	feet NGVD (1929)
S7SHALL	Shallow Well Water Elevation	feet NGVD (1929)
S7D_TEMP	Deep Well Water Temperature	degrees Celsius
S7S_TEMP	Shallow Well Water Temperature	degrees Celsius
T_STG	Tailwater Stage	feet NGVD (1929)
HEADTEMP	Headwater Temperature	degrees Celsius
HEADPH	Headwater pH	none
HEADCOND	Headwater Specific Conductivity	µS/cm
HEADDO	Headwater Dissolved Oxygen	mg/l
TAILTEMP	Tailwater Temperature	degrees Celsius
TAILPH	Tailwater pH	none
TAILDCOND	Tailwater Specific Conductivity	µS/cm
TAILDO	Tailwater Dissolved Oxygen	mg/l
ENG_RPM	Combined Pump Station Engine Speed	rpm
BAROM	Barometric Pressure (Boynton Beach)	in mercury (Hg)
HDDIFF	Headwater/Deep Well Water Level Differences	feet
DSDIFF	Deep Well/Shallow Well Water Level Differences	feet
TDDIFF	Tailwater/Deep Well Water Level Differences	feet
TSDIFF	Tailwater/Shallow Well Water Level Differences	feet
THDIFF	Tailwater/Headwater Water Level Differences	feet
DSGRAD	Deep Well/Shallow Well Gradient	none
SHGRAD	Shallow	well/headwater gradient
HDGRAD	Headwater/Deep Well Gradient	none
VEL1	USGS Velocity Station 1	feet per second
VEL2	USGS Velocity Station 2	feet per second
VELAVG	Velocity of Station 1 and 2 Averaged	feet per second
SCONDDP	Corrected Specific Conductivity Deep Well	S/cm
SCONDSH	Corrected Specific Conductivity Shallow Well	S/cm

Water Quality Data for Period 1

Dissolved Oxygen

During Period 1, September 14 to October 10, 1995, headwater DO values ranged from 0.04 to 1.71 mg/l with a mean of 0.53 mg/l (n = 1,423) (**Appendix C**, **Figure C-2**). Several upward spikes were the normal diurnal DO fluctuations in the canal. The tailwater DO range was from at or near 0.04 to 2.52 mg/l with a mean of 0.69 mg/l (n = 1,415). Tailwater DO levels were generally 1 mg/l higher than the headwater side of the pump station and may be reflective of lower gradients and/or aeration effects from pumping. Headwater and tailwater DO values generally equilibrated during pumping operations (**Appendix C**, **Figure C-2**).

The batteries in both the tailwater and headwater sensors expired on September 29, 1995. The sensors were refitted with new batteries and recalibrated before the passing of Hurricane Opal on October 3, 1995.

Specific Conductivity

The SC in the deep well ranged from 892 to 1,945 µS/cm with a mean of 1,034 µS/cm (n = 2,623) and the SC in the shallow groundwater well ranged from 464 to 1,338 µS/cm with a mean of 647 µS/cm (n = 2,623). The water quality data are summarized in **Table 10**. The deep groundwater SC levels were fairly stable throughout the period (**Appendix C**, **Figure C-3**), except for several large unexplainable spikes. During a period of four readings (1 hour), one reading was 897 µS/cm, and another reading was 1,945 µS/cm. The spikes were attributed to electronic noise interference from the water level transducer in the same well. The SC in the headwater and the tailwater were generally less than 1,200 µS/cm (**Appendix C, Figure C-7**).

Water Quality Data for Period 2

Dissolved Oxygen

During Period 2, October 11 to November 7, 1995, the headwater DO levels were generally lower than the tailwater DO levels. The DO for the headwater ranged about 0.04 to 1.81 mg/l with a mean of 0.63 mg/l (n = 1,861). The DO for the tailwater ranged about 0.07 to 2.12 mg/l with a mean of 0.83 mg/l (n = 1,608). Headwater and tailwater DO values generally equilibrated during pumping operations (**Appendix C**, **Figure C-7**).

Average DO values were about 0.137 mg/l from October 11 to October 14, 1995, with several spikes above 1.0 mg/l (**Appendix C**, **Figure C-2**). These upward spikes were due to diurnal DO fluctuations in the headwater and tailwater canals.

During the pumping activity that occurred from October 17 to October 23, 1995, the headwater DO seldom exceeded the tailwater DO, with the tailwater DO levels generally being 1 mg/l higher on the tailwater side of the pump station than on the headwater side.

Both Hydrolab™ sensors were removed for an annual Quality Assurance/Quality Control (QA/QC) check from October 24 to October 30, 1995. The sensors were returned, refitted with new batteries, and recalibrated the final week of the study: October 30, 1995, to November 7, 1995.

Specific Conductivity

The deep groundwater SC levels were fairly stable throughout the period (**Appendix C**, **Figure C-3**), except after the large pumping event from October 14, 1995, to October 24, 1995 (**Appendix C**, **Figure C-9**), at which time both the shallow and deep wells had reduced SC because of rainfall recharge. The range for the deep well SC was 898 to 1,260 µS/cm with a mean of 1,032 µS/cm (n = 2,633). The shallow groundwater well SC showed generally twice the amplitude of variations as compared to the deep well amplitudes of SC. The shallow well SC ranged from 496 to 986 µS/cm, with a mean of 645 µS/cm (n = 2,633).

SC in the headwater and the tailwater continued to be less than 1,200 µS/cm (occasionally exceeding 1,275 µS/cm) and never fell below 500 µS/cm (**Appendix C**, **Figure C-4**). The range for the headwater side SC was 603 to 1,240 µS/cm with a mean 843 µS/cm (n = 1,859). The tailwater SC ranged from 537 to 1,098 µS/cm with a mean of 856 µS/cm (n = 1,607). The water quality data are summarized in **Table 10**.

DISCUSSION

The S-7 Pump Station operational impacts on the nearby hydrologic regime involves many dynamic processes. The scenarios (high water levels, pump on, pump off, etc.) examined in this study helped to determine general trends in the data. Through reviewing these trends, an understanding of the ground and surface water quality conditions at the headwater side of the pump station under static and dynamic conditions was developed. Water quality conditions in the pump station headwater are controlled by surface water inflow, by water levels within the aquifer, and by the headwater-tailwater level differential. To understand water movement at the site, water level differences and gradients were calculated between the headwater, tailwater, and wells when the pumps were both on and off (**Table 13**).

Water Levels

Several gradient reversals occurred during the study period between the deep and shallow monitor wells and the headwater as seen in **Table 13** and **Figure C-5** in **Appendix C**. Throughout the study period, groundwater from the shallow portion of the aquifer always discharged into the headwater side of the pump station because a positive hydraulic gradient existed. Net mean gradients from the shallow well to the headwater ranged from 0.0038 to 0.0063, regardless of pump status. The net deep well and shallow well gradients were always recharging, except during Period 2 when the pumps were on. The net mean gradients for the deep well and shallow well ranged from -0.013 to -0.0007, indicating a downward recharge (**Appendix B, Figure B-2**), while the net upward

Table 13. Tabulated Summary of Mean Water Level Gradients, DO, and SC at the S-7 Pump Station as a Function of Pump Operation

Parameter	Mean Gradient Headwater Level Compared to Deep Well Water Level	Mean Gradient Deep Well Water Level Compared to Shallow Well Water Level	Mean Gradient Shallow Well Water Level Compared to Headwater Level	Mean Dissolved Oxygen (mg/l)	Mean Specific Conductivity (µS/cm)
	+ = upward discharge - = downward recharge	+ = upward discharge - = downward recharge	+ = Aquifer to canal - = Canal to aquifer	H = Headwater T = Tailwater	H = Headwater T = Tailwater D = Deep well S = Shallow well
Period 1					
Pumps On	+0.0041	-0.003	+0.005	0.72 (H) 0.76 (T)	940 (H) 949 (T) 1,024 (D) 637 (S)
Pumps Off	-0.0084	-0.0133	+0.0038	0.42 (H) 0.66 (T)	806 (H) 905 (T) 1,040 (D) 653 (S)
Period 2					
Pumps On	+0.0128	+0.0026	+0.0063	0.86 (H) 1.09 (T)	885 (H) 858 (T) 1,031 (D) 606 (S)
Pumps Off	+0.0050	-0.0007	+0.0038	0.35 (H) 0.53 (T)	792 (H) 853 (T) 1,043 (D) 690 (S)

recharge gradient was +0.0026 when the pump was on during Period 2 (**Appendix B, Figure B-3**). Gradients in the headwater-deep well were discharging upward throughout the study period, with the exception of Period 1, when the pumps were off. The range for the net upward gradient was from +0.0041 to +0.0050, while the net downward gradient during Period 2 was -0.0084. Generally, pumping operations increased the gradients and discharge between the canal and the deep well, with the exception of Period 1. At this time, pumping caused the gradient to reverse because the surface water elevations were higher than the deep well water levels.

Dissolved Oxygen

The net surface water DO measurements indicated continuously low levels of oxygen in both the headwater and tailwater during this investigation (**Table 11**). Suppressed DO levels are a function of the upstream canal inflow DO concentration, groundwater inflow and its DO concentration, canal biological oxygen demand (BOD), canal chemical oxygen demand (COD), sediment oxygen demand (SOD), and water clarity. The influence of each factor on low DO concentrations measured was not addressed in this investigation. During pumping operations, the net DO levels were elevated about 0.2 mg/l. The DO levels in all the pumping scenarios were below 1.0 mg/l (**Appendix C, Figure C-6**), with the exception of one tailwater DO measurement of 1.09 mg/l when the pumps were on. During this investigation the mean engine rpm was 496 with a maximum of 2,040 rpm.

Elevated DO levels during pumping are likely due to turbulence-induced aeration. Discrepancies occurred between the long-term historical wet season DO monitoring data and data collected during this investigation. Long-term wet season DO levels had only eight deviations less than 1.0 mg/l in 1,127 samples for the entire 20-year period of record (1973 to 1993). In contrast, during this investigation, 4,551 samples fell between 0.0 and 1.0 mg/l, and 705 samples fell between 1.0 and 2.0 mg/l (**Appendix C, Figure C-7)**. We believe the location(s) at which surface water samples were collected historically at the pump station could have been a factor influencing the difference between the historical DO data and DO concentrations measured during this investigation.

Specific Conductivity

It appears that both the headwater and tailwater are influenced by the shallow and deep groundwater. However, more water from the deep well is pulled to the surface when the pump is on. The mean SC of the headwater and tailwater is 870 µS/cm when the pump is on and 825 µS/cm when the pump is on (**Table 11**). Possible long-term SC levels are a function of the upstream canal inflow, upstream surface water and groundwater, and the canal sediment thickness.

The mean SC levels of the headwater, tailwater, and wells are presented in **Table 13**. The mean headwater SC increased from 806 to 940 µS/cm and from 792 to 885 µS/cm during Periods 1 and 2, respectively, when the pumps were on. These data support the hypothesis that higher conductivity groundwater flows into the canal headwater area when the pumps are running. Tailwater SC also increased slightly during pumping.

CONCLUSIONS

Based on the information collected for this short-term investigation at the SFWMD's S-7 pump station, the following conclusions were formulated for the period from September 13 to November 7, 1995:

- The operation of the pump station caused significant mixing of groundwater (deep and shallow) and surface water in the headwater side of the pump station. This is because SC levels of the headwater increased to the average SC values of the deep and shallow wells.
- The DO levels in the headwater were very low, with a mean of 0.59 mg/l (n = 3,284), while the tailwater mean was slightly higher at 0.77 mg/l (n = 3,023). The lowest DO levels and stratification occurred when the pump was off.
- The United States Geological Survey (USGS) velocity profiles on the headwater side of the pump station indicated a negative velocity away from the pump station during high tailwater elevations. This negative velocity was confirmed by USGS staff in Miami and further confirms the underflow (seepage) from the tailwater side of the pump station to the headwater side when a difference of greater than three feet exists between the two. It

should be noted that all pumps are equipped with back flow preventives eliminating any significant siphoning or back flow.

- Pumping elevated the DO levels from 0.25 to 0.75 mg/l in the immediate vicinity of the pump station due to turbulence and aeration effects of the pump. DO levels were slightly higher on the headwater side of the pump station, but pumping influence on DO was observed on both sides.
- The shallow well water levels correlated best with the surface water DO concentrations (-0.3645). The shallow well water level was inversely related to the DO concentration in the headwater side of the structure. The shallow well water level and the headwater always had a positive net discharge to the canal regardless of pumping activity.
- The deep well water levels seemed to have limited influence on DO concentrations. This could be a function of the chronically low levels of surface water or to a limited connection between the headwater elevations and the deep well water levels.
- The SC of the headwater was inversely related to water levels in the shallow well, as was the case with the DO. At higher shallow aquifer levels, seepage and interflow increase, but the SC of the groundwater was diluted from rainfall effects.
- The correlation of the SC of the deep well to the shallow well SC (0.650) was inversely related to the tailwater level (-0.322) and the deep well water level (-0.234). Although these relationships are not direct correlations, they do indicate a role in influencing the results. The correlations are also supported by the upward gradients in the groundwater wells to the surface water.
- Preliminary information indicates that vertical stratification of DO (top 1 to 2 feet of the headwater) and SC are taking place during cycles when the pumps are not operating at the S-7 Pump Station. This stratification is destroyed during pumping events. This is supported by evidence of the headwater SC equaling the SC of the deep well during pumping events. After pumping events, the headwater conductivity returns to the background level of the shallow well or slightly above that background level.
- During periods when the difference between the headwater and tailwater sides is greater than 3.7 feet (**Table 9**), data indicates a significant exchange between the tailwater, groundwater, and the headwater sides of the pump station. This effects the headwater water quality sampling and the overall results.

RECOMMENDATIONS

All water quality sampling at the headwater side of the S-7 Pump Station should be moved to a new location upstream. This site should have a dedicated walkway protruding into the canal and should be away from the influence of pump station activity. This would prevent the application of state water quality standards for surface water to samples that are overly influenced by groundwater quality.

When performing sampling required by permit at the S-7 Pump Station, the following precautions should be taken:

- Collection of the water quality samples at the headwater side of the pump station should not be done unless the headwater-tailwater differential is less than 3.7 feet.
- Samples should be collected while the pumps are running.
- Headwater and tailwater elevations from the manual staff gages should be recorded in the field notebooks and associated to the sample in the laboratory's water quality or DBHYDRO databases. This would assist in future analysis of water quality data and in future water quality modeling.
- Collection of canal water quality parameters should be conducted at different times (i.e., day/night, afternoon/morning, and during storm events) to accommodate seasonality, storm events, and irregular daylight and evening events.
- Manually-read shallow well piezometers should be installed at all surface water sampling locations to record groundwater levels during the sampling event.

A plan should be developed for investigating other pump stations and their effects on water quality. The plan should include a discussion on the shortfalls of this short S-7 investigation (i.e., DO and SC profiles to measure upward fluxes and discharges were not performed) and potential improvements. The plan should address use of seepage meters (manual or electronic) in channel piezometers and the use of tracers to determine travel times of the underflow and lateral seepage components. The plan should include drilling of groundwater wells, sampling protocol methodologies, and long-term monitoring strategies.

REFERENCES

Belanger, T.V., and H. Heck. 1994. *Dissolved Oxygen Field Studies in the Kissimmee River System.* C-3205, Florida Institute of Technology, Melbourne, FL.

LTI. 1995. *Data Analysis in Support of the Everglades Forever Act.* Final Report to South Florida Water Management District from Limno-Tech, Inc., West Palm Beach, FL.

USACE. 1955. Agricultural Land Conservation Area's Supplement 24. *Design Memorandum, Pump Station 7*. Serial Number 22, United States Army Corps of Engineers, Jacksonville, FL.

APPENDIX A

HISTORICAL DISTRIBUTION OF DISSOLVED OXYGEN AND SPECIFIC CONDUCTIVITY

This appendix provides histograms of the historical distribution of DO (**Figures A-1** through **A-12**) and SC (**Figures A-13** through **A-24**) for pump stations during wet and dry seasons. Histograms of DO and SC in the S-7 Pump Station headwaters during the investigation are shown in **Figures A-25** and **A-26**, respectively.

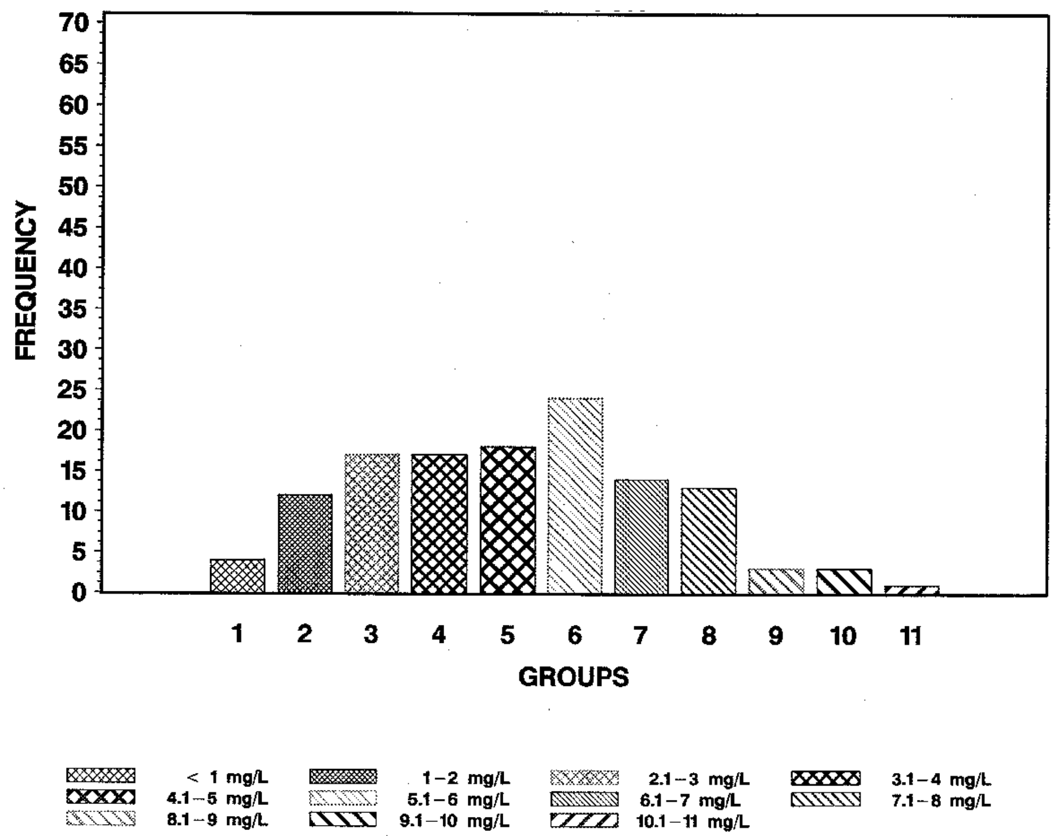


Figure A-1. Histogram of the Historical Distribution of Dissolved Oxygen for the S-5A Pump Station during the Dry Season for the Period of Record (1979 to 1993)

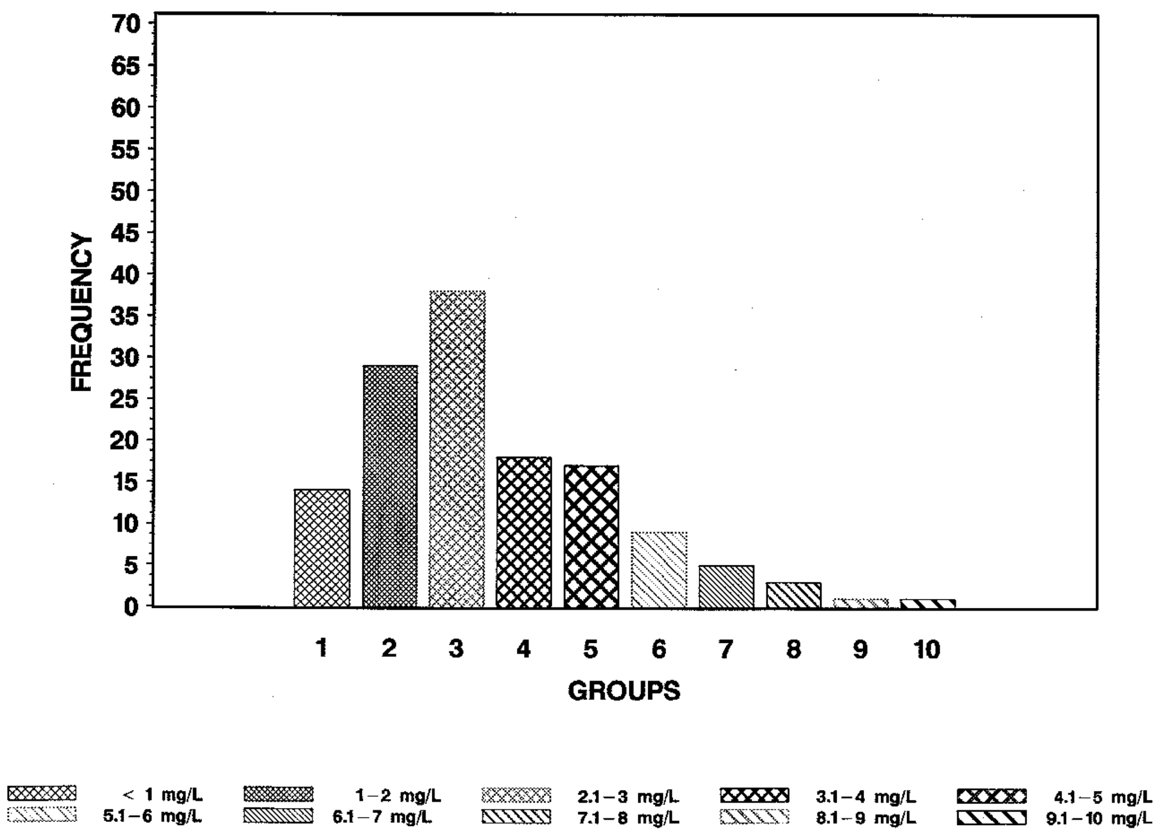


Figure A-2. Histogram of the Historical Distribution of Dissolved Oxygen for the S-5A Pump Station during the Wet Season for the Period of Record (1979 to 1993)

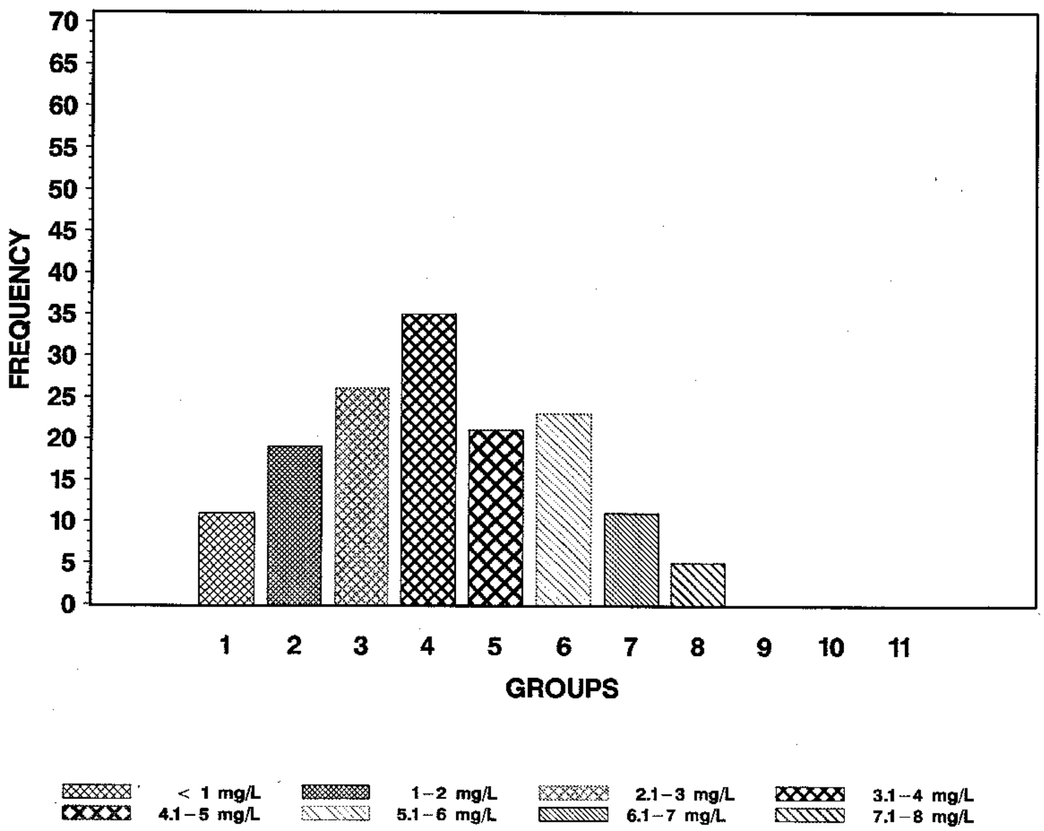


Figure A-3. Histogram of the Historical Distribution of Dissolved Oxygen for the S-6 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

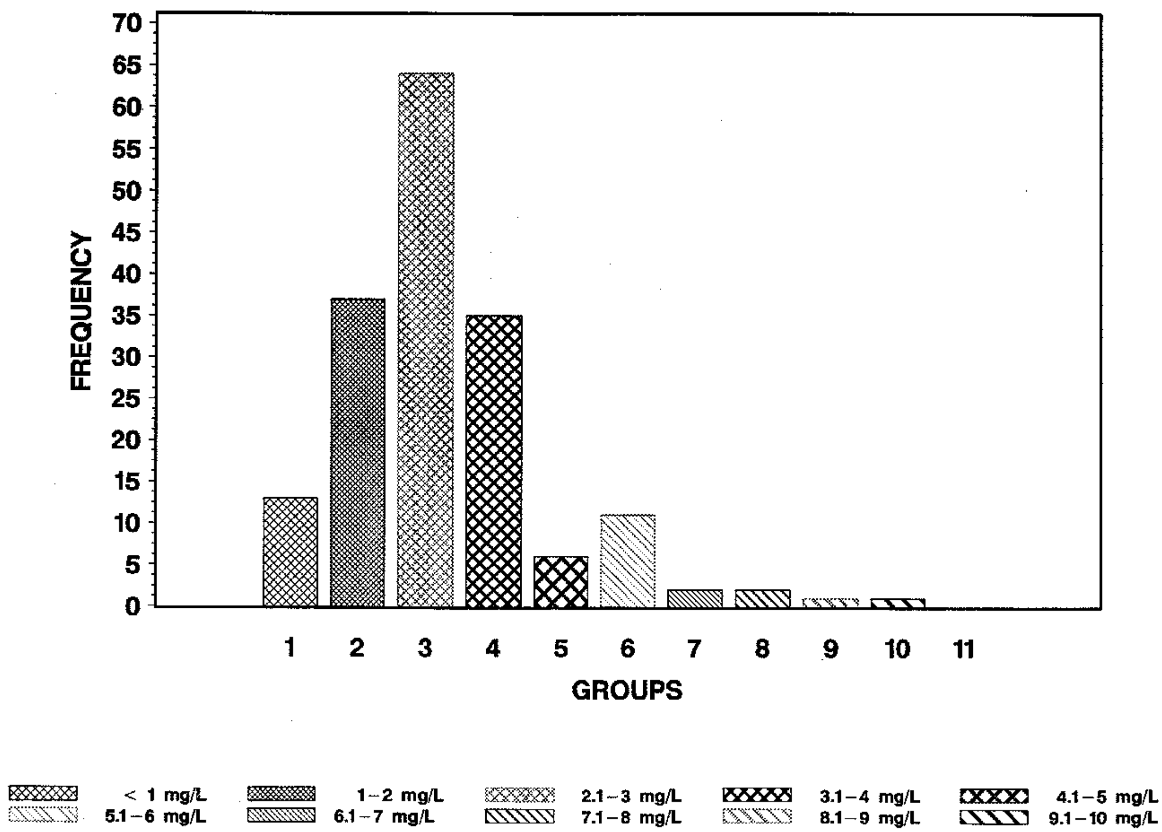


Figure A-4. Histogram of the Historical Distribution of Dissolved Oxygen for the S-6 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

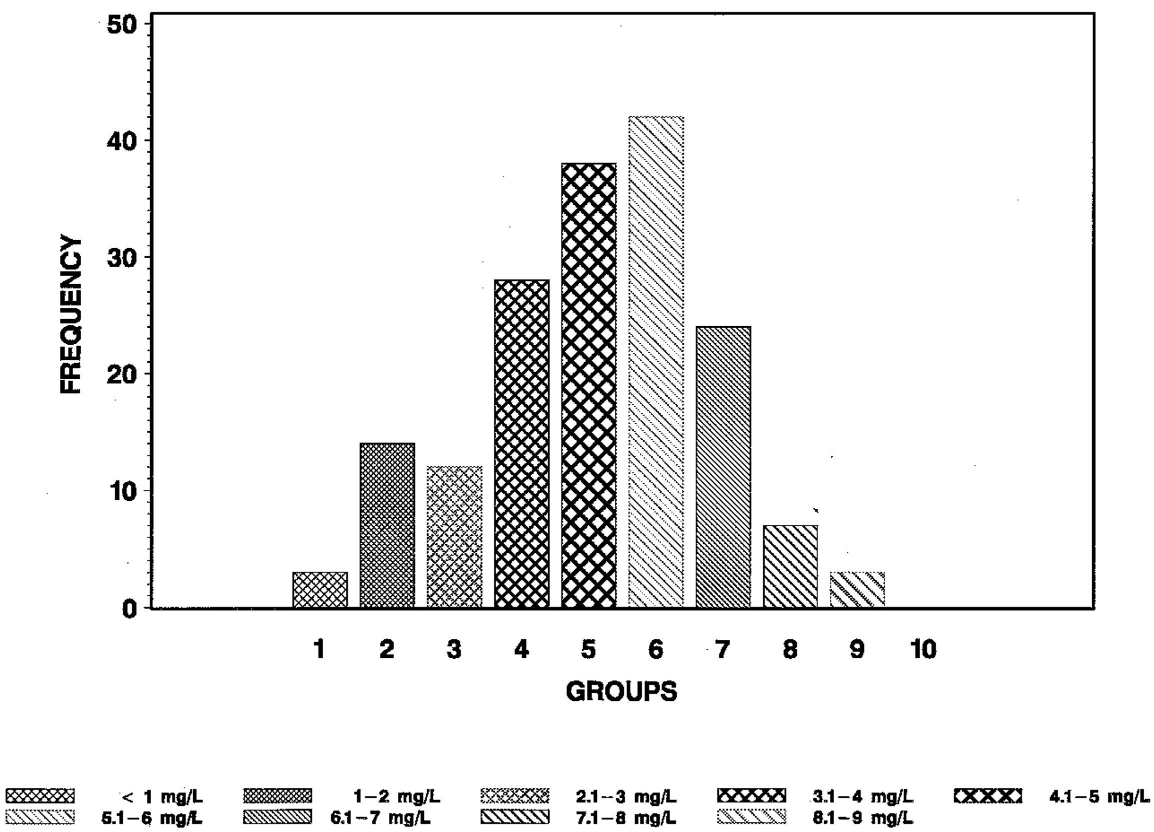


Figure A-5. Histogram of the Historical Distribution of Dissolved Oxygen for the S-7 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

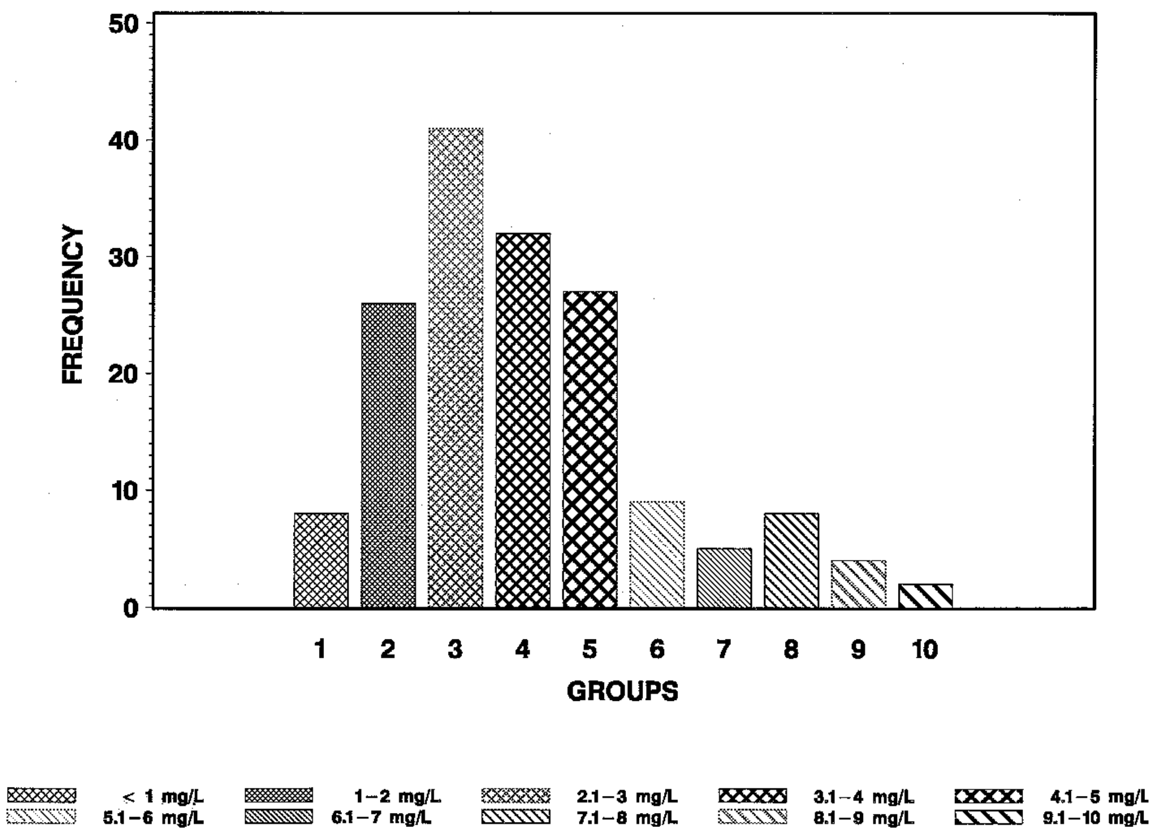


Figure A-6. Histogram of the Historical Distribution of Dissolved Oxygen for the S-7 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

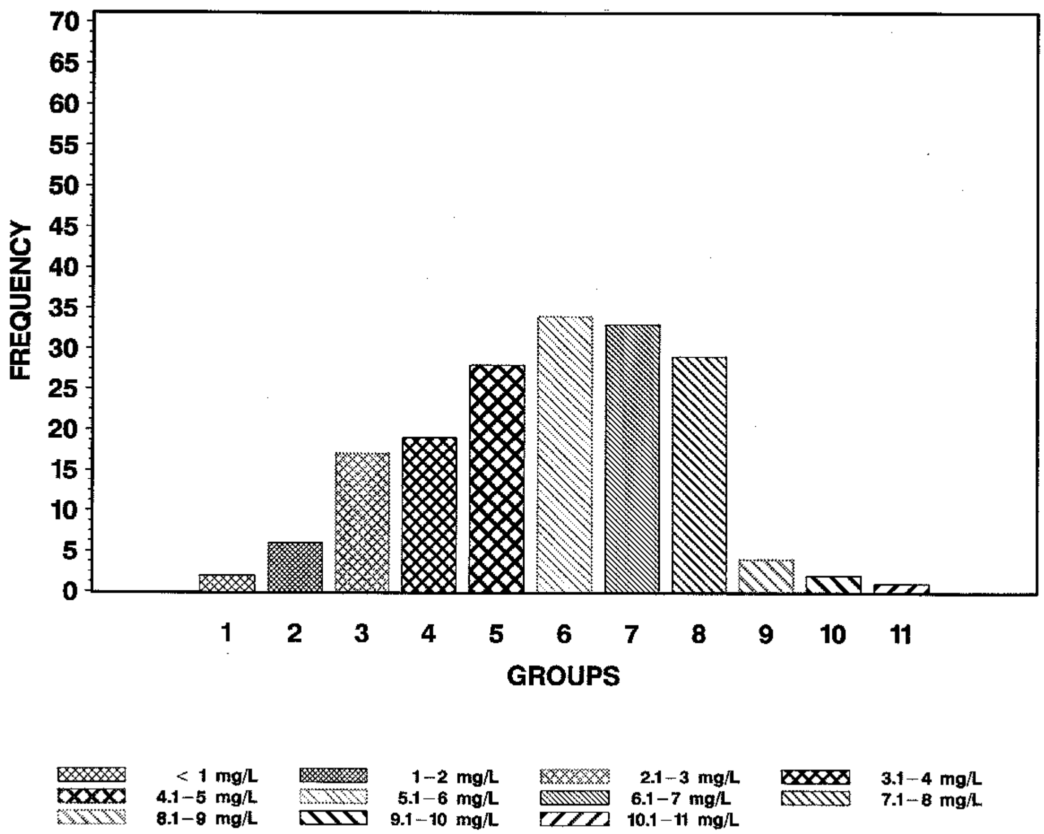


Figure A-7. Histogram of the Historical Distribution of Dissolved Oxygen for the S-8 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

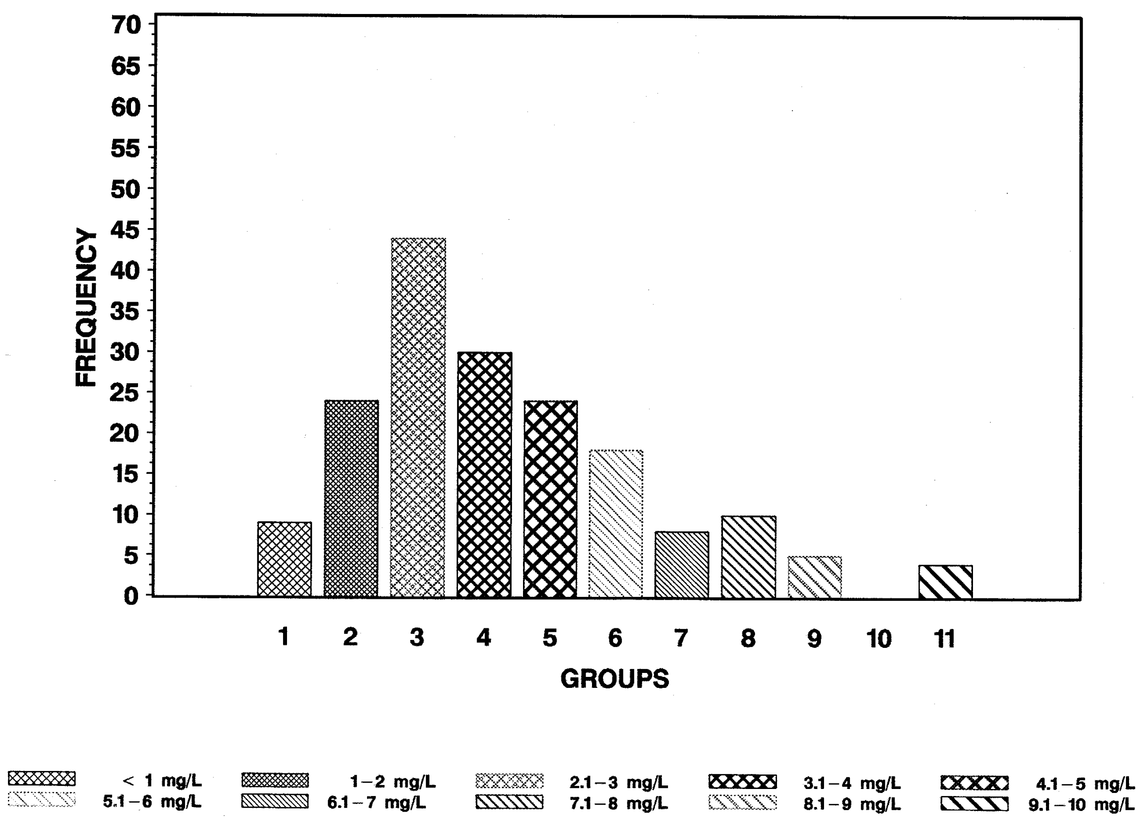


Figure A-8. Histogram of the Historical Distribution of Dissolved Oxygen for the S-8 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

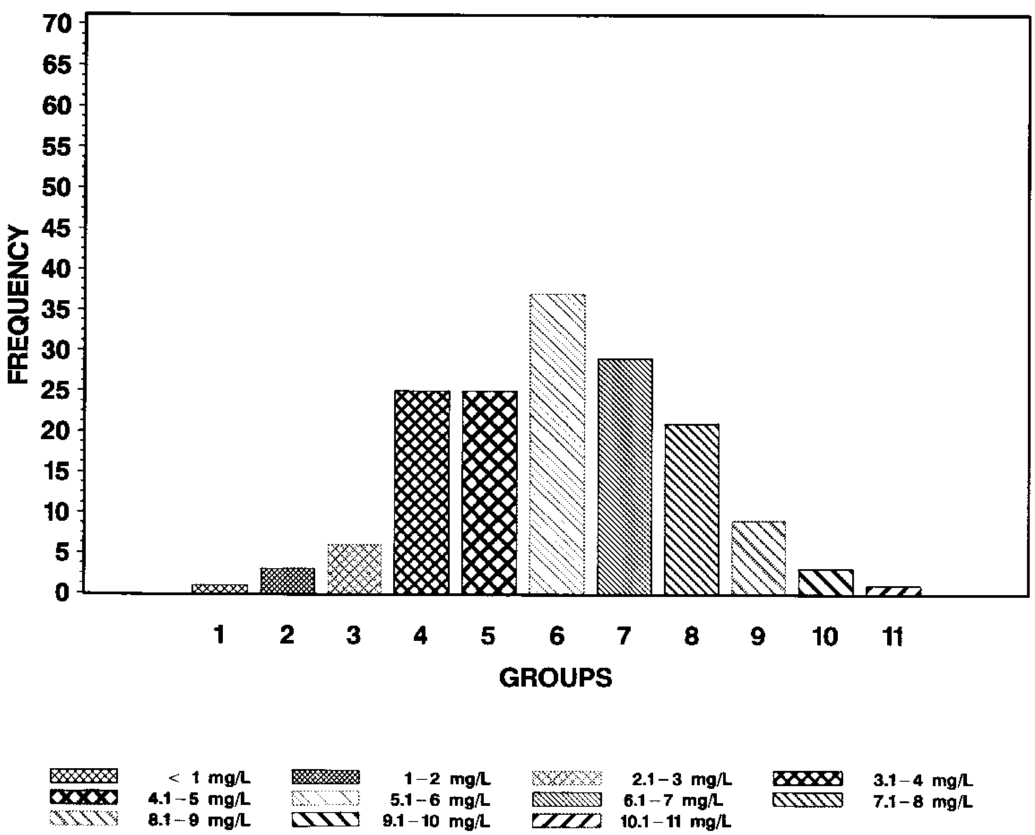


Figure A-9. Histogram of the Historical Distribution of Dissolved Oxygen for the S-140 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

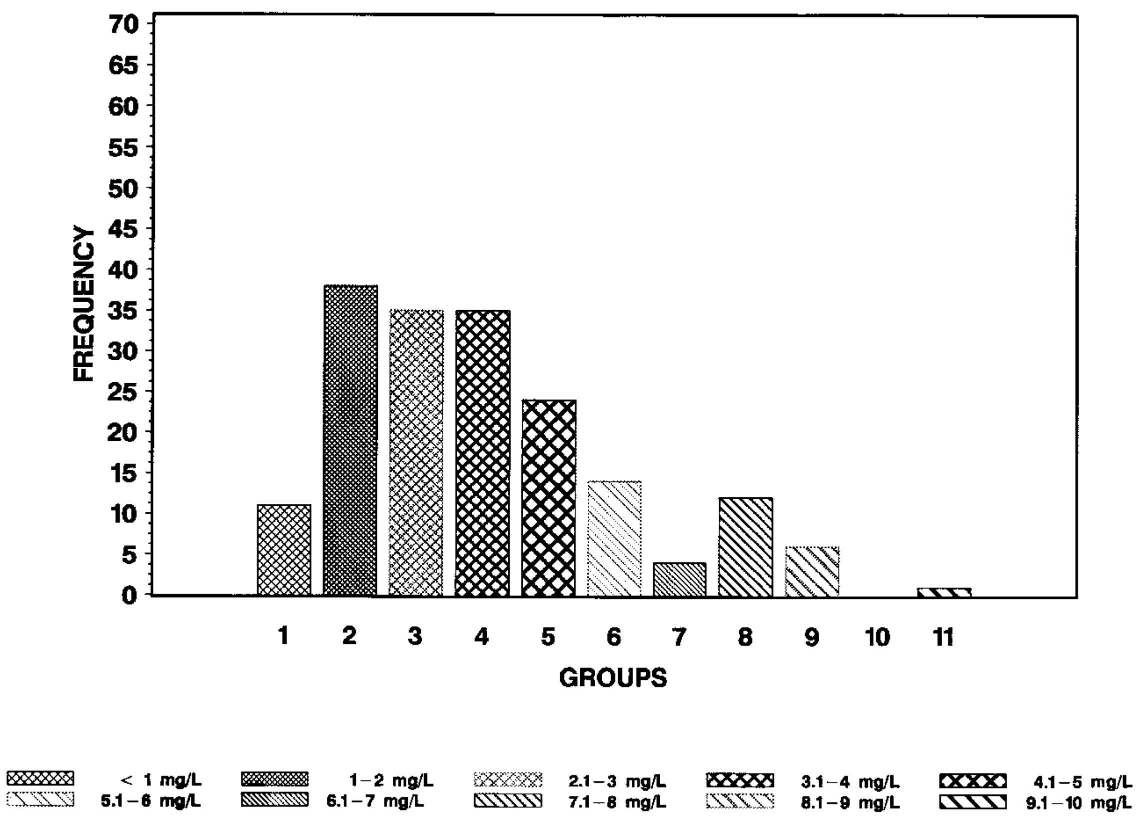


Figure A-10. Histogram of the Historical Distribution of Dissolved Oxygen for the S-140 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

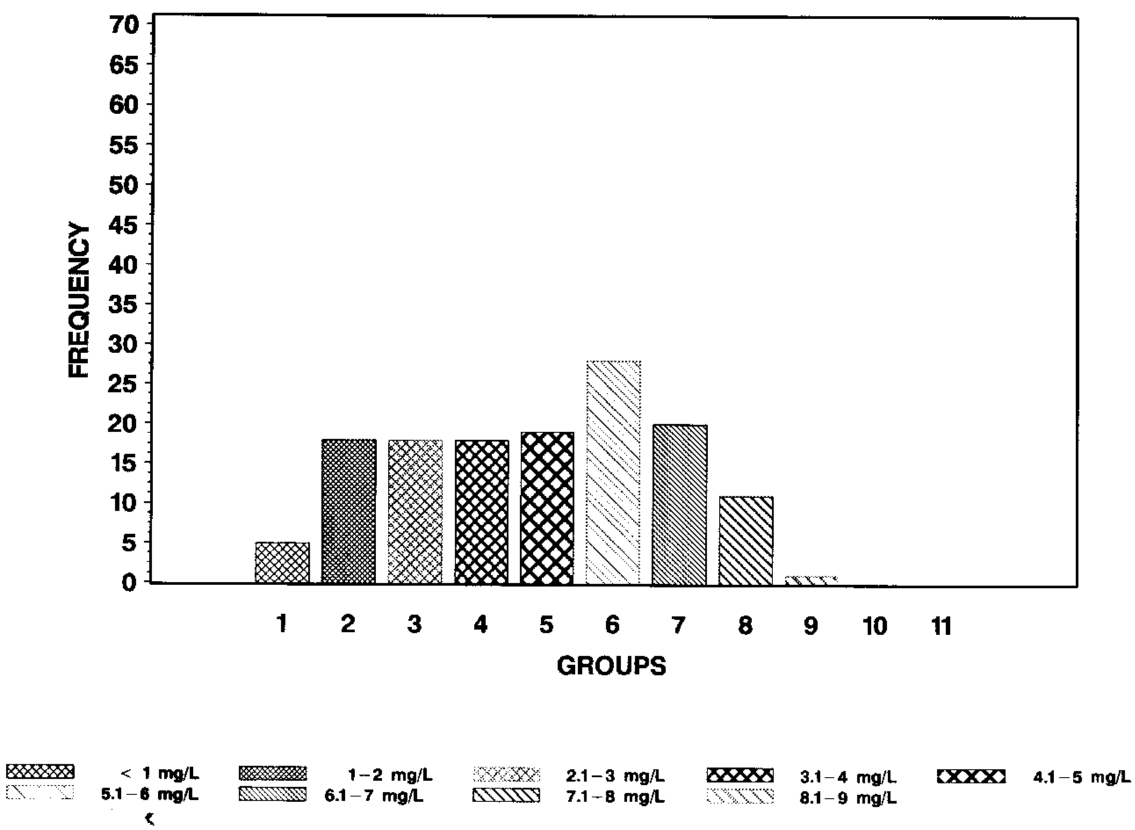


Figure A-11. Histogram of the Historical Distribution of Dissolved Oxygen for the S-332 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

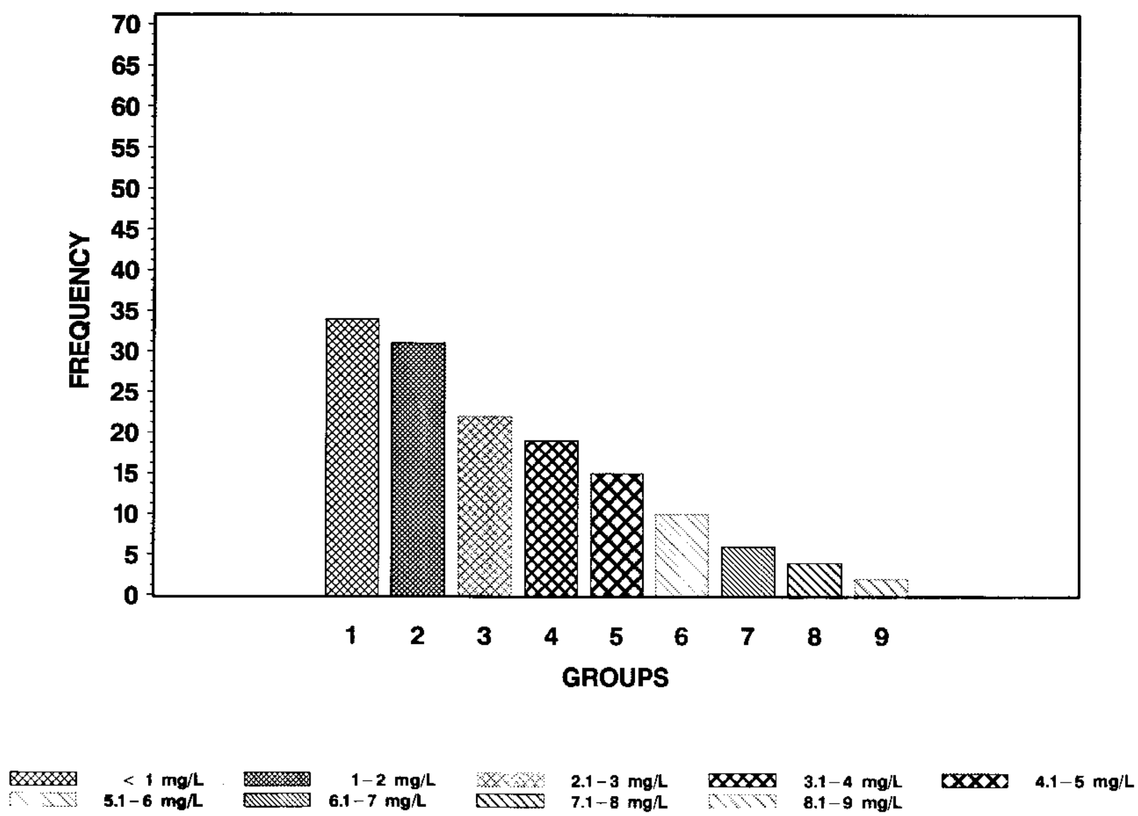


Figure A-12. Histogram of the Historical Distribution of Dissolved Oxygen for the S-332 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

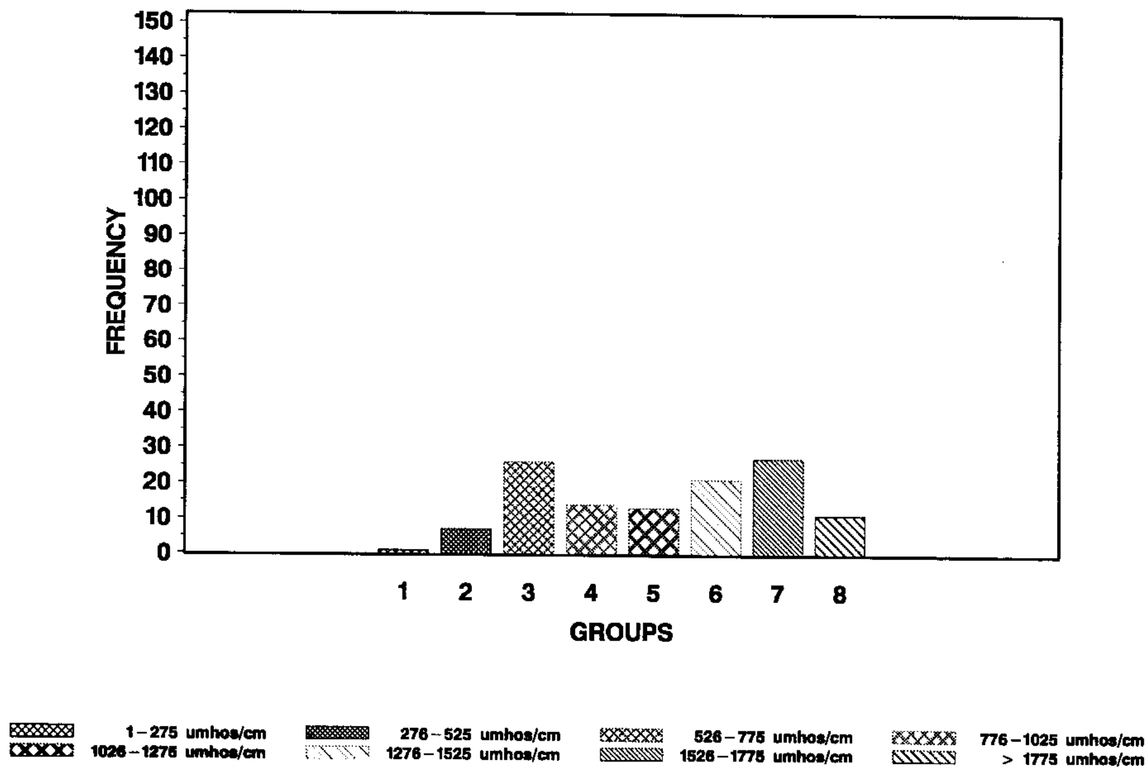


Figure A-13. Histogram of the Historical Distribution of Specific Conductivity for the S-5A Pump Station during the Dry Season for the Period of Record (1979 to 1993)

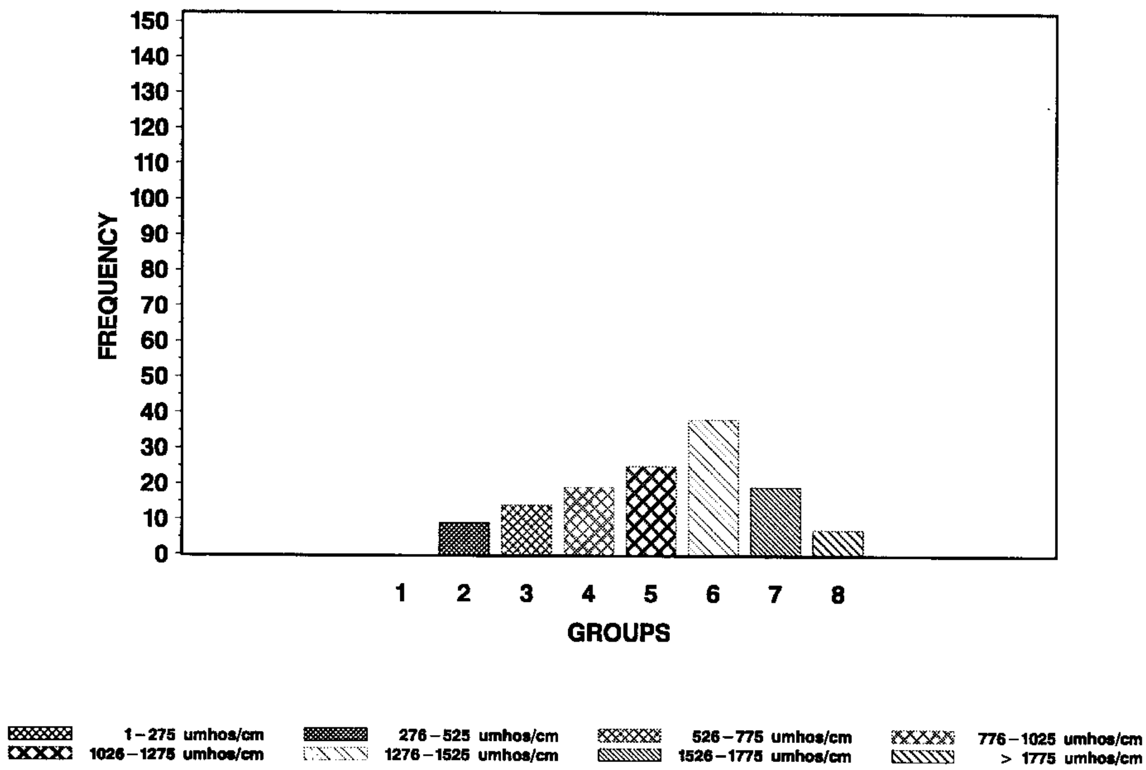


Figure A-14. Histogram of the Historical Distribution of Specific Conductivity for the S-5A Pump Station during the Wet Season for the Period of Record (1979 to 1993)

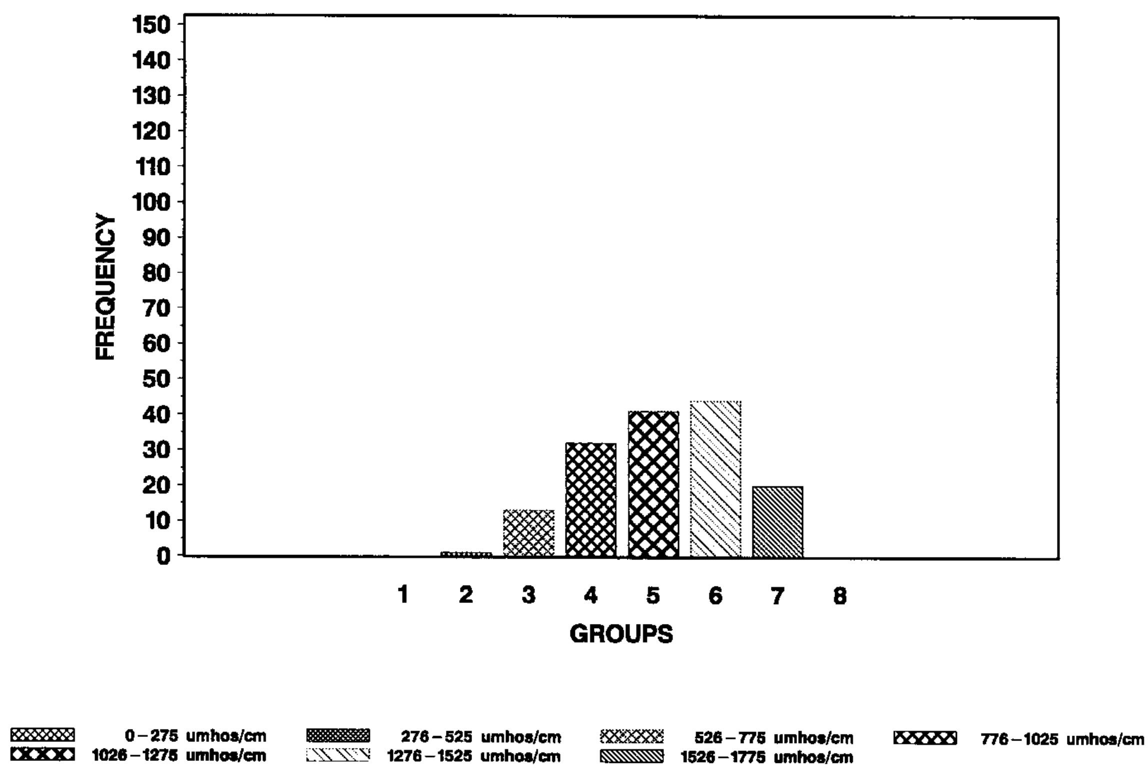


Figure A-15. Histogram of the Historical Distribution of Specific Conductivity for the S-6 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

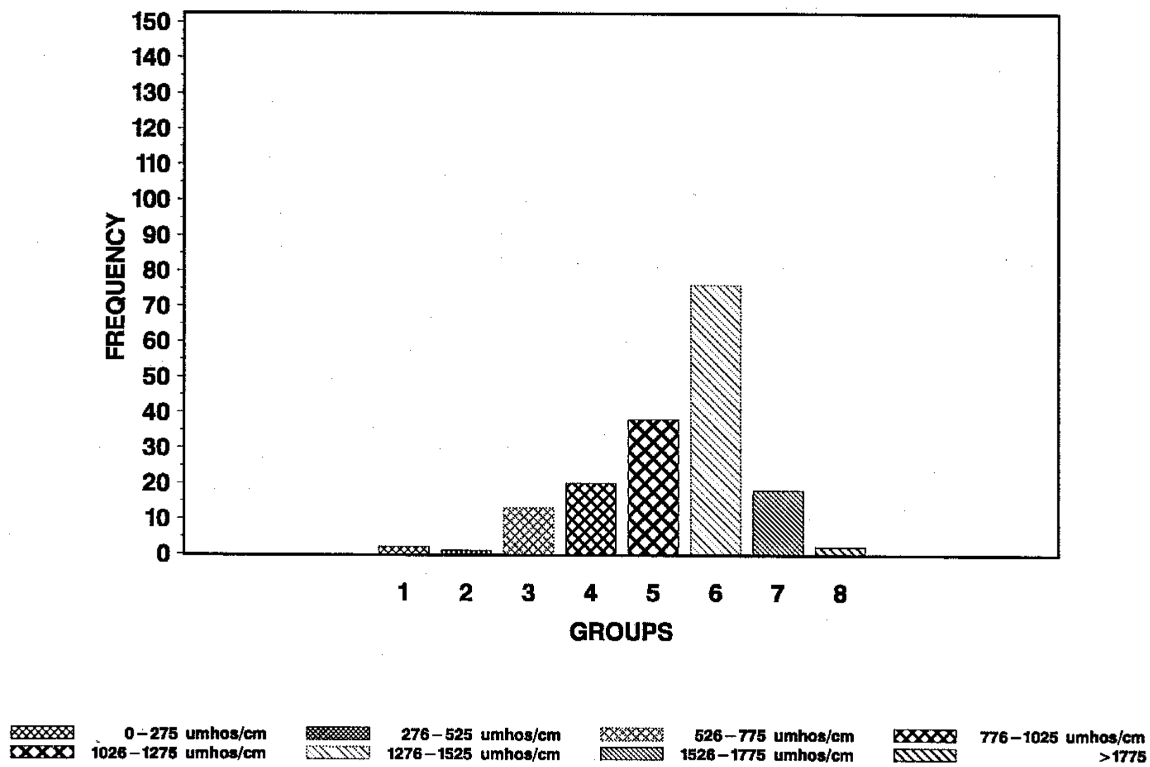


Figure A-16. Histogram of the Historical Distribution of Specific Conductivity for the S-6 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

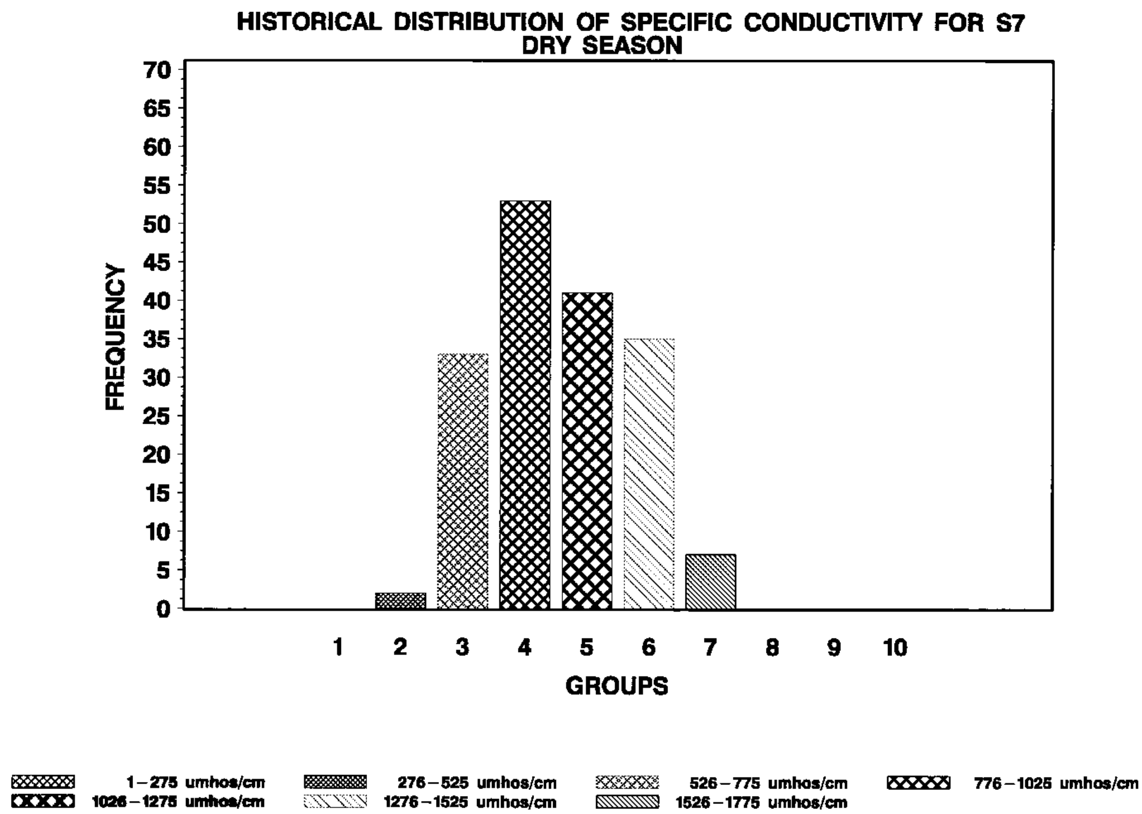


Figure A-17. Histogram of the Historical Distribution of Specific Conductivity for the S-7 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

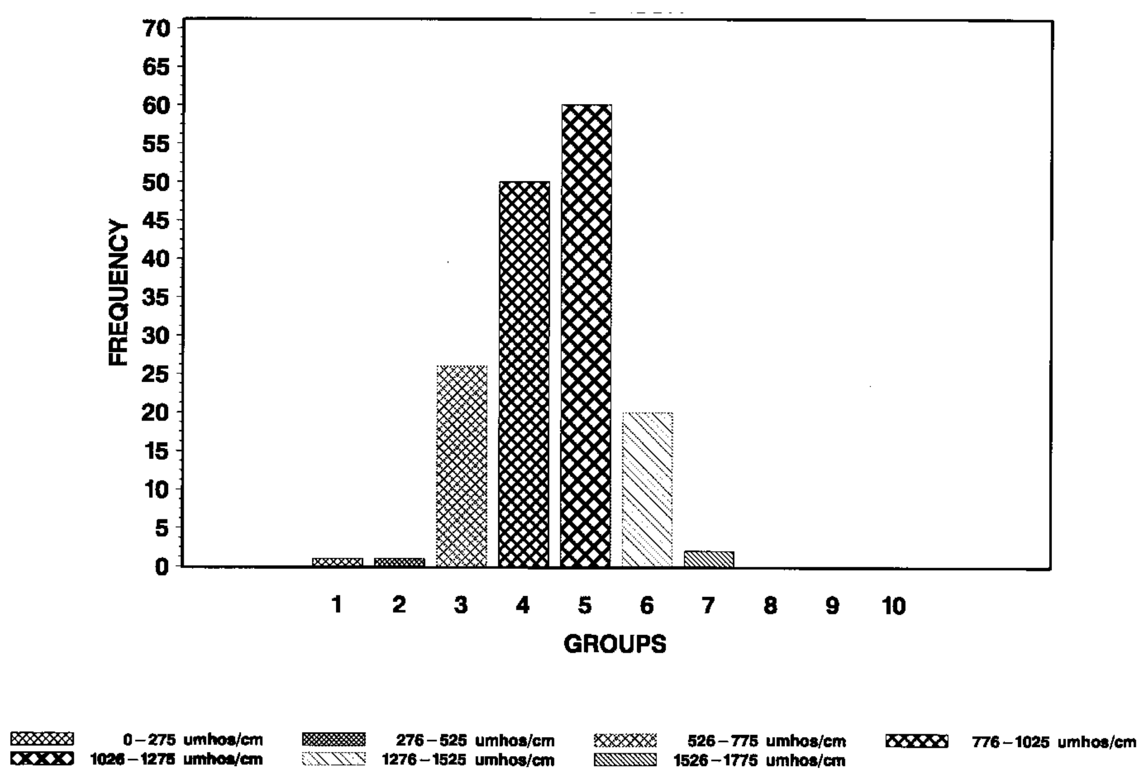


Figure A-18. Histogram of the Historical Distribution of Specific Conductivity for the S-7 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

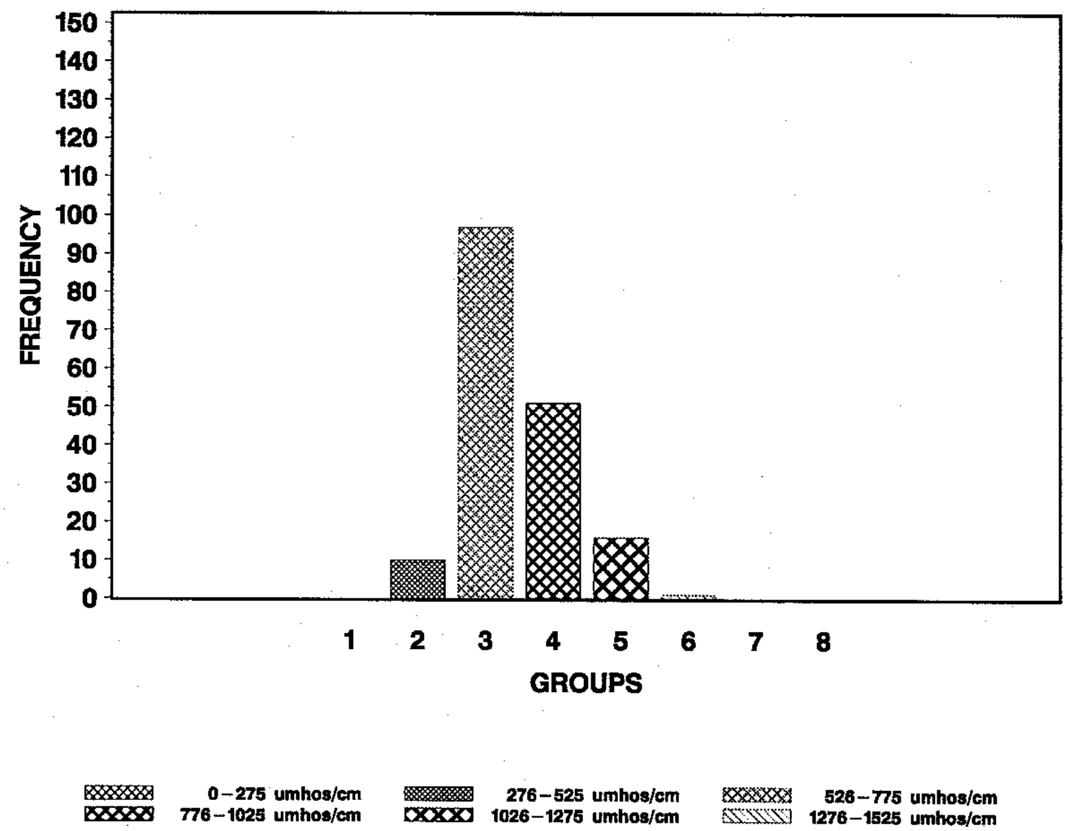


Figure A-19. Histogram of the Historical Distribution of Specific Conductivity for the S-8 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

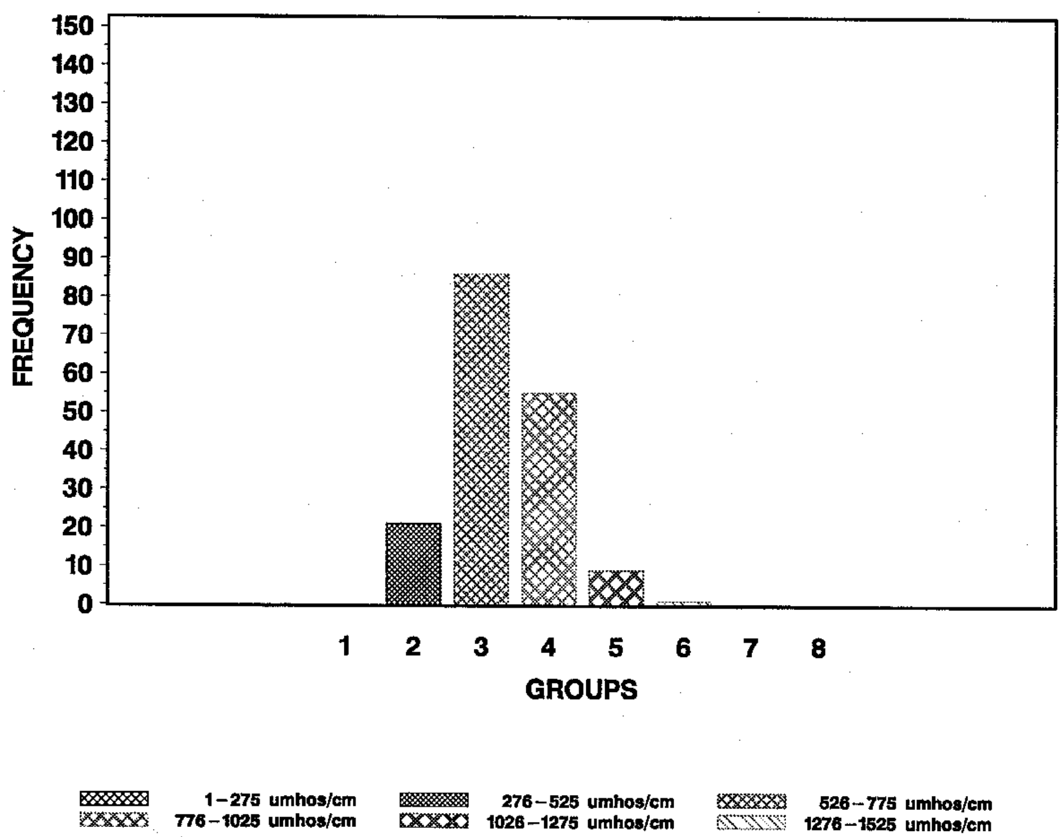


Figure A-20. Histogram of the Historical Distribution of Specific Conductivity for the S-8 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

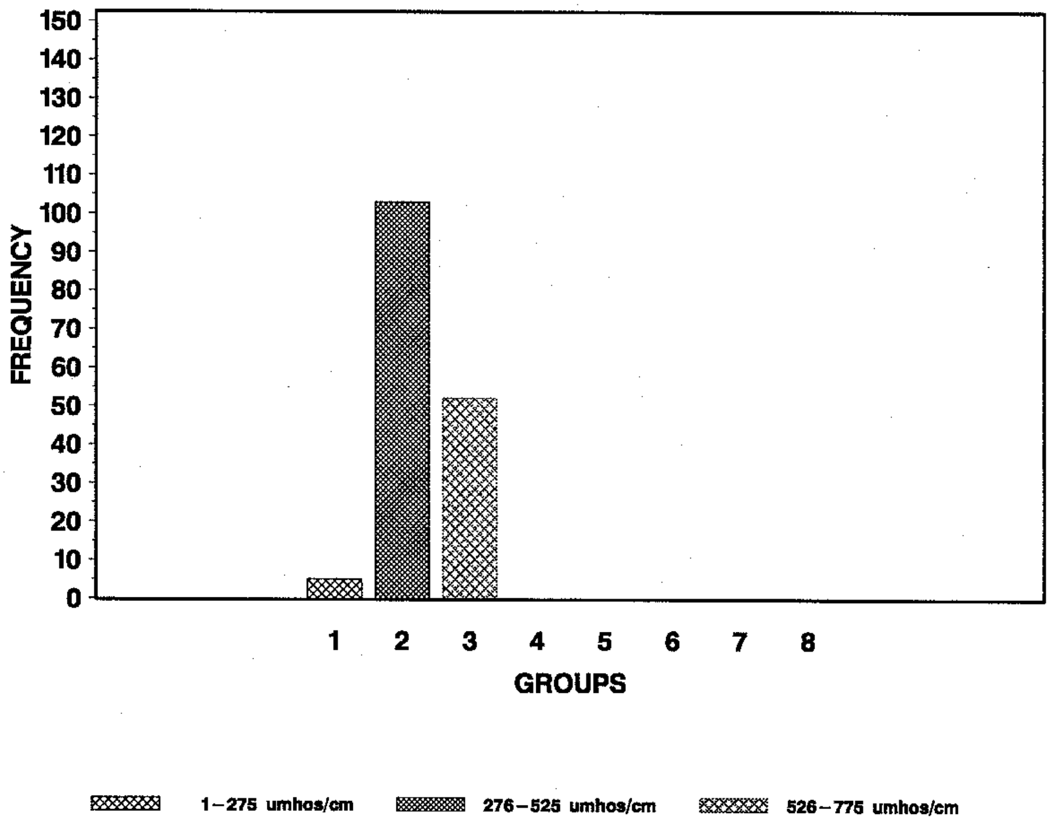


Figure A-21. Histogram of the Historical Distribution of Specific Conductivity for the S-140 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

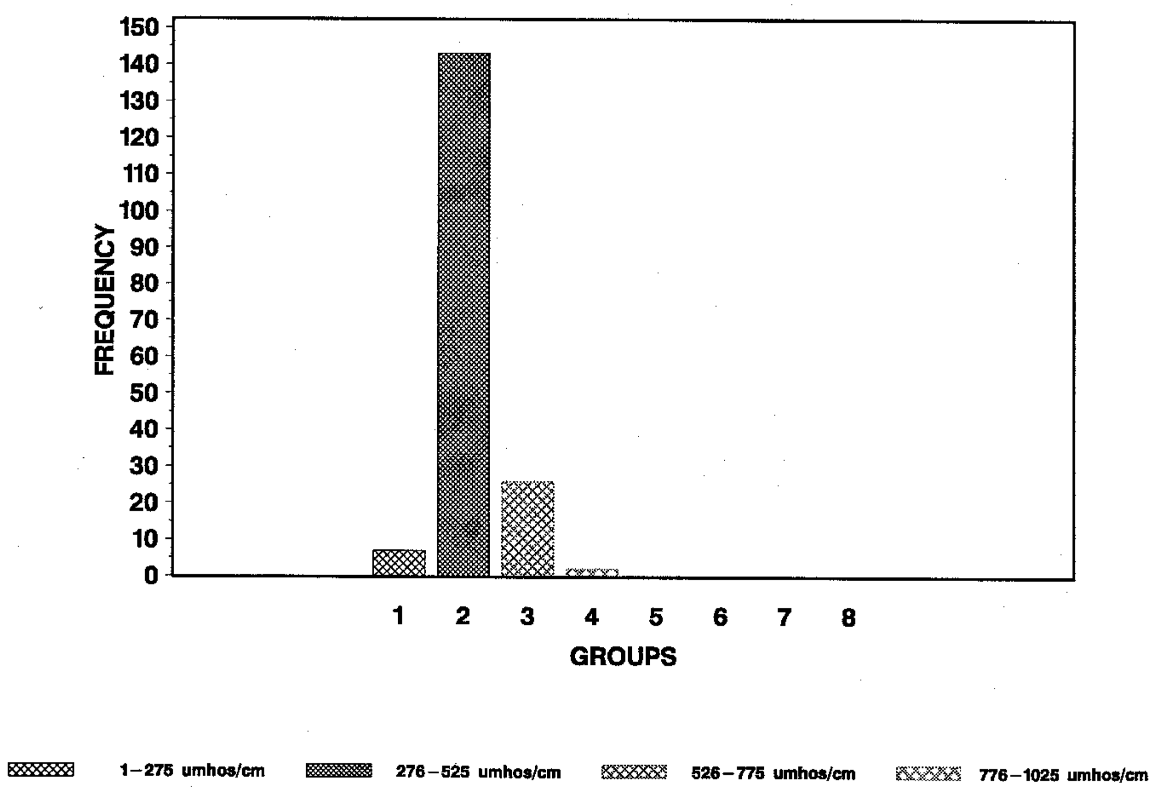


Figure A-22. Histogram of the Historical Distribution of Specific Conductivity for the S-140 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

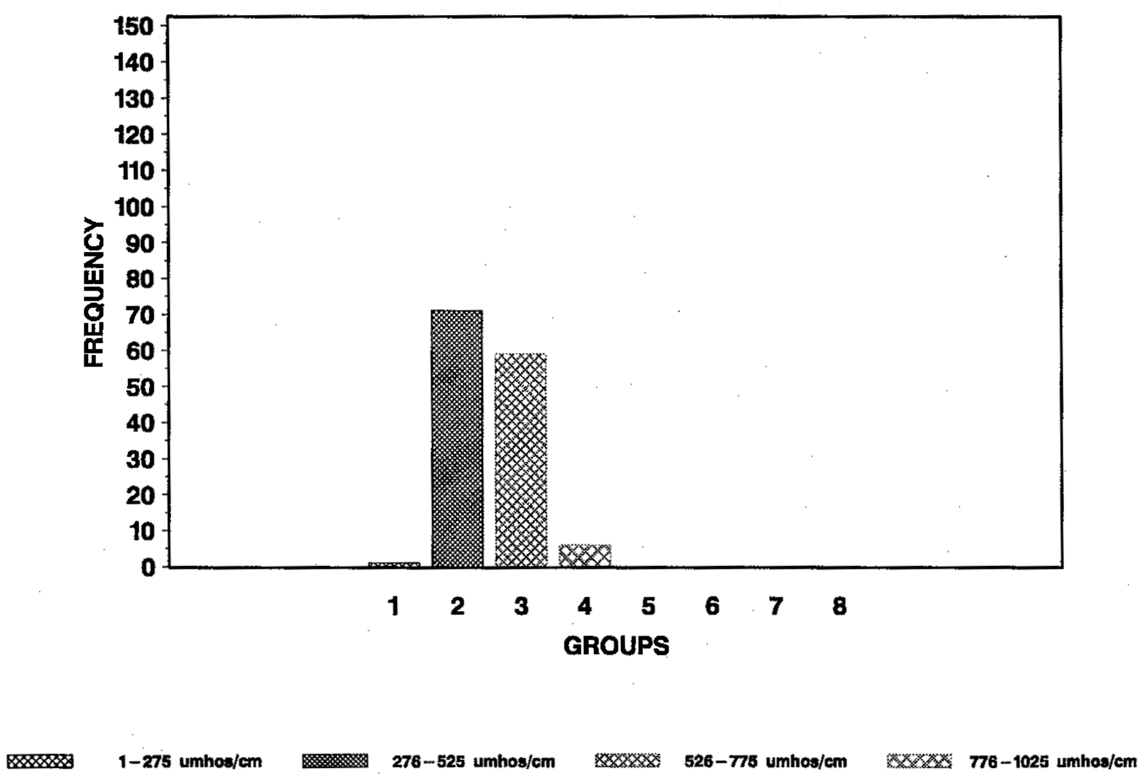


Figure A-23. Histogram of the Historical Distribution of Specific Conductivity for the S-332 Pump Station during the Dry Season for the Period of Record (1979 to 1993)

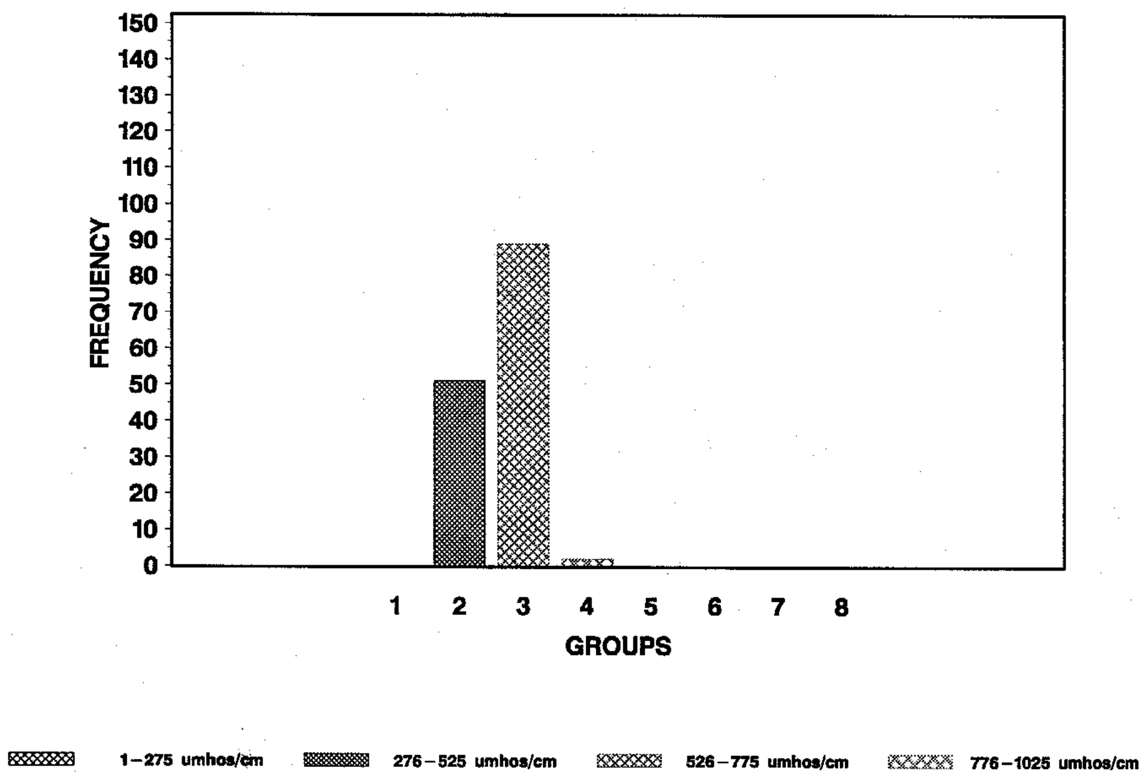


Figure A-24. Histogram of the Historical Distribution of Specific Conductivity for the S-332 Pump Station during the Wet Season for the Period of Record (1979 to 1993)

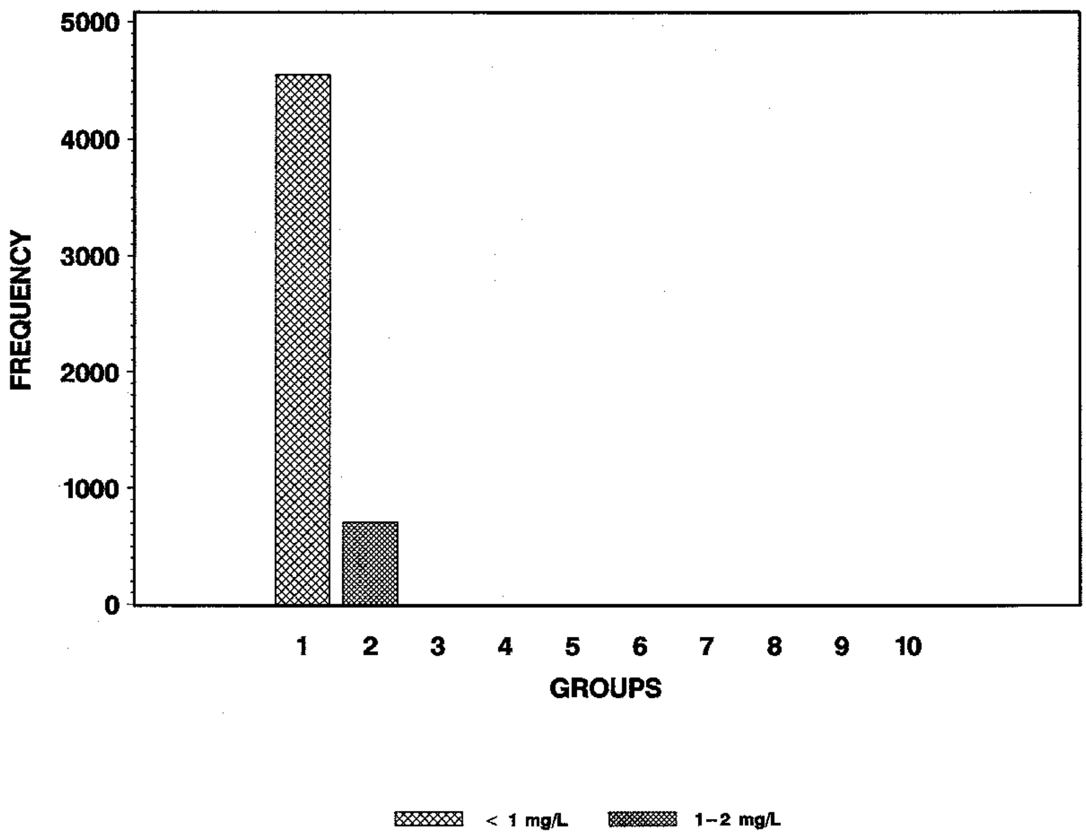


Figure A-25. Histogram of Dissolved Oxygen Field Data Collected in the Headwaters of the S-7 Pump Station during the Investigation

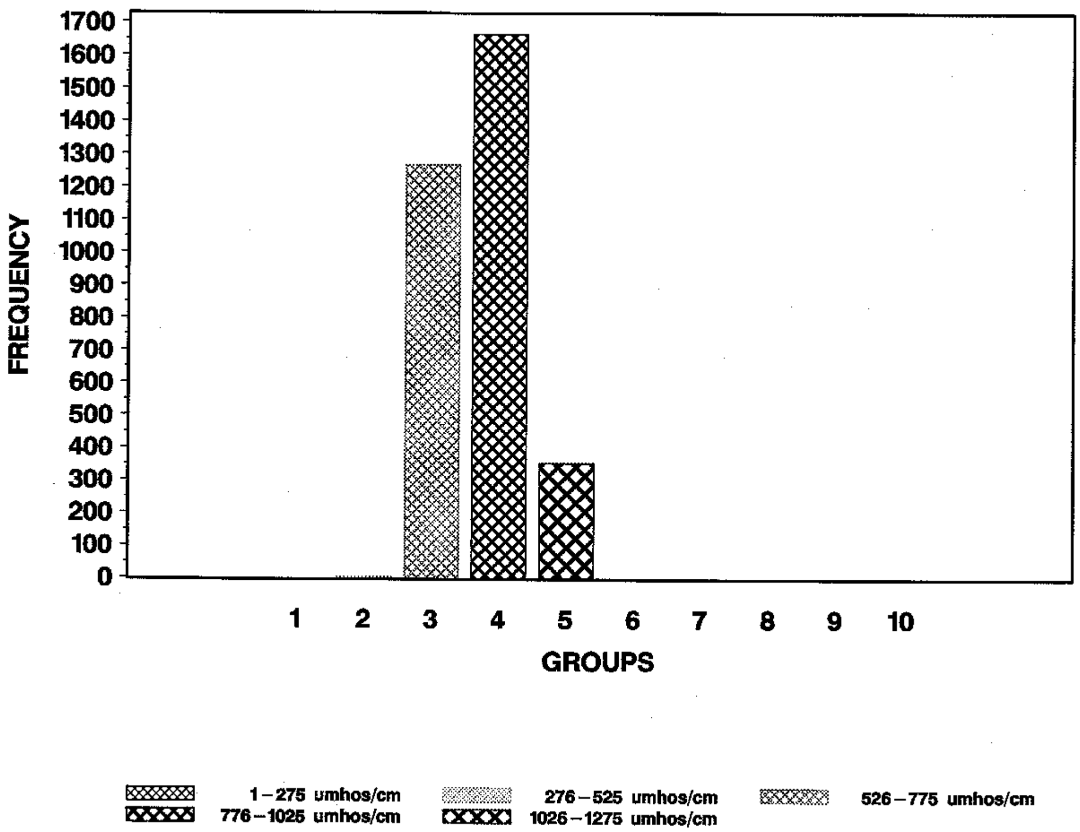


Figure A-26. Histogram of Dissolved Oxygen Field Data Collected in the Headwaters of the S-7 Pump Station during the Investigation

APPENDIX B

S-7 PUMP STATION FIELD INVESTIGATION CROSS-SECTIONS AND LOGS

This appendix provides a site map (**Figure B-1**) of the geologic cross-sections used in the text. **Figures B-5** and **B-3** depict graphical cross-sections of the pump stations showing groundwater flow paths. The lithologic log printout of well WCAS-7D shown in **Figure B-2**, depicts samples drilled from 0 to 100 feet.

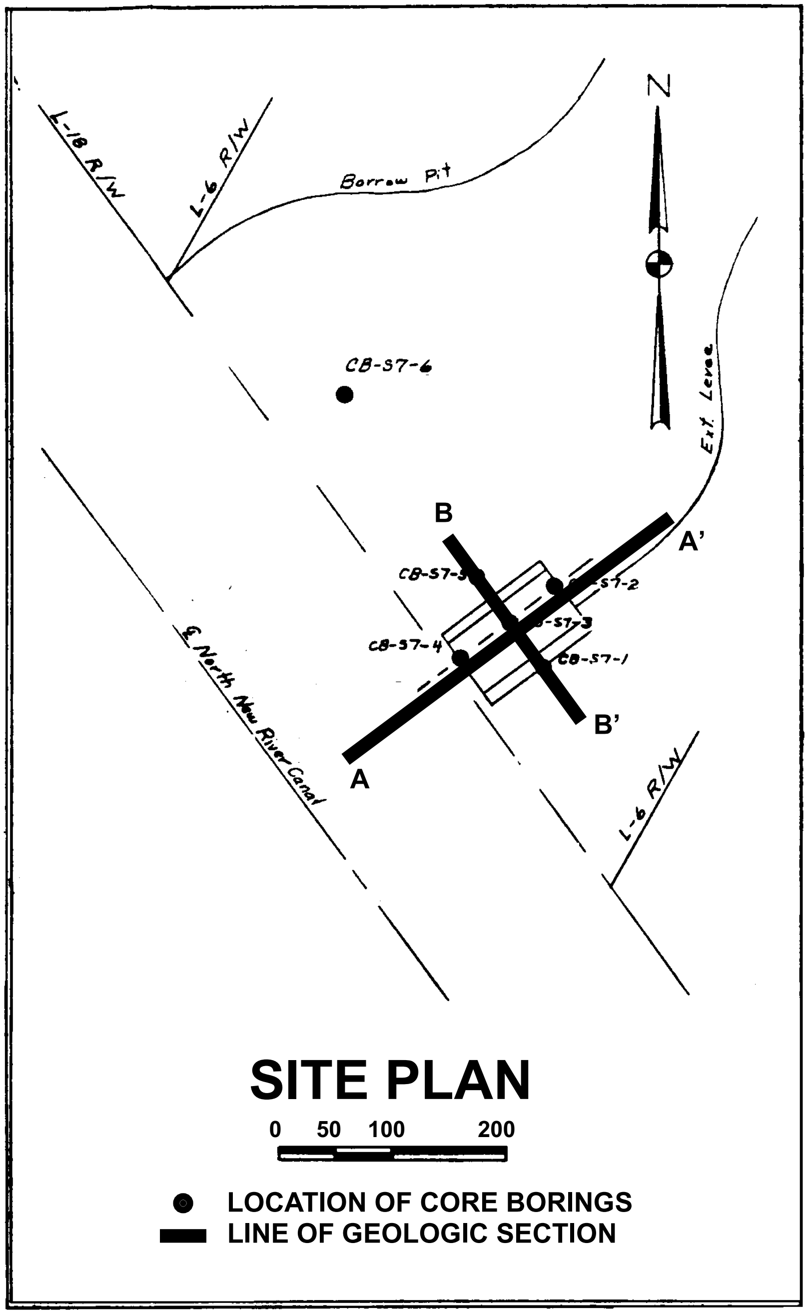


Figure B-1. Site Plan View for United States Army Corps of Engineers Geologic Cross-Sections

```
LITHOLOGIC WELL LOG PRINTOUT                    SOURCE - FGS    WCAS-7Deep

WELL NUMBER:   W-17041                          COUNTY -   PALMBEAC
TOTAL DEPTH:      100  FT.                      LOCATION:  T.47S R.38E S.20
10 SAMPLES FROM 0 TO 100 FT.                               LAT = 26D 20M 06S
                                                           LON = 80D 32M 14S
COMPLETION DATE: N/A                            ELEVATION: 10 FT
OTHER TYPES OF LOGS AVAILABLE - OTHER

OWNER/DRILLER:SOUTH FLORIDA WATER MANAGEMENT DISTRICT

WORKED BY:__JOE AYLOR (1/28/94), 10 FOOT SAMPLE INTERVALS.
SFWMD ID# FOR CUTTINGS IS 099-72 (HOLE #WCAS-7D) PALM BEACH COUNTY
LOCATED IN THE 0E 1/4, 0E 1/4, 0E 1/4 SEC 00, T46S, R39E.
UTM PLANAR, ZONE 17 X=546182.7; Y=2912702.4
FLORIDA EAST ZONE IN FEET, POLYCONIC PLANAR X=651577.1; PLANAR Y=727733.7
WELL IS LOCATED IN THE EVERGLADES 1 SE 7.5 MINUTE QUADRANGLE.
THE OKEECHOBEE FORMATION IS PROPOSED FOR THE PLIO-PLEISTOCENE INTERVAL
(SCOTT, 1992, P. 23, FLORIDA GEOLOGICAL SURVEY SPECIAL PUBLICATION 36).

   0.   -     .   121PCPC   PLIOCENE-PLEISTOCENE

   0  -   20   CALCILUTITE; GRAYISH BROWN
               20% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
               GRAIN TYPE: BIOGENIC, CALCILUTITE
               90% ALLOCHEMICAL CONSTITUENTS
               GRAIN SIZE: VERY FINE; RANGE: MICROCRYSTALLINE TO FINE
               POOR INDURATION
               CEMENT TYPE(S): CALCILUTITE MATRIX
               ACCESSORY MINERALS: PLANT REMAINS-20%, SHELL-20%
               OTHER FEATURES: WEATHERED
               FOSSILS: MOLLUSKS, FOSSIL FRAGMENTS
               20% BLACK ORGANICS.

  20  -   70   SHELL BED; MODERATE LIGHT GRAY
               30% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
               UNCONSOLIDATED
               ACCESSORY MINERALS: QUARTZ SAND-20%
               FOSSILS: MOLLUSKS, FOSSIL FRAGMENTS
               GASTROPODS.

  70  -   80   LIMESTONE; MODERATE LIGHT GRAY TO LIGHT OLIVE GRAY
               20% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
               GRAIN TYPE: BIOGENIC, CALCILUTITE
               95% ALLOCHEMICAL CONSTITUENTS
               GRAIN SIZE: VERY FINE; RANGE: MICROCRYSTALLINE TO FINE
               MODERATE INDURATION
               CEMENT TYPE(S): CALCILUTITE MATRIX
               ACCESSORY MINERALS: SHELL-30%, QUARTZ SAND-20%
               FOSSILS: MOLLUSKS, FOSSIL FRAGMENTS
               GASTROPODS.
```

Figure B-2. Lithologic Well Log Printout

```
 80  -  100   LIMESTONE; YELLOWISH GRAY TO LIGHT GREENISH GRAY
              20% POROSITY: INTERGRANULAR, POSSIBLY HIGH PERMEABILITY
              POOR INDURATION
              CEMENT TYPE(S): CALCILUTITE MATRIX
              ACCESSORY MINERALS: SHELL-40%, QUARTZ SAND-30%
              OTHER FEATURES: COQUINA
              FOSSILS: MOLLUSKS, FOSSIL FRAGMENTS, ECHINOID
              GASTROPODS.

100  TOTAL DEPTH
```

Figure B-4. Lithologic Well Log Printout (Continued)

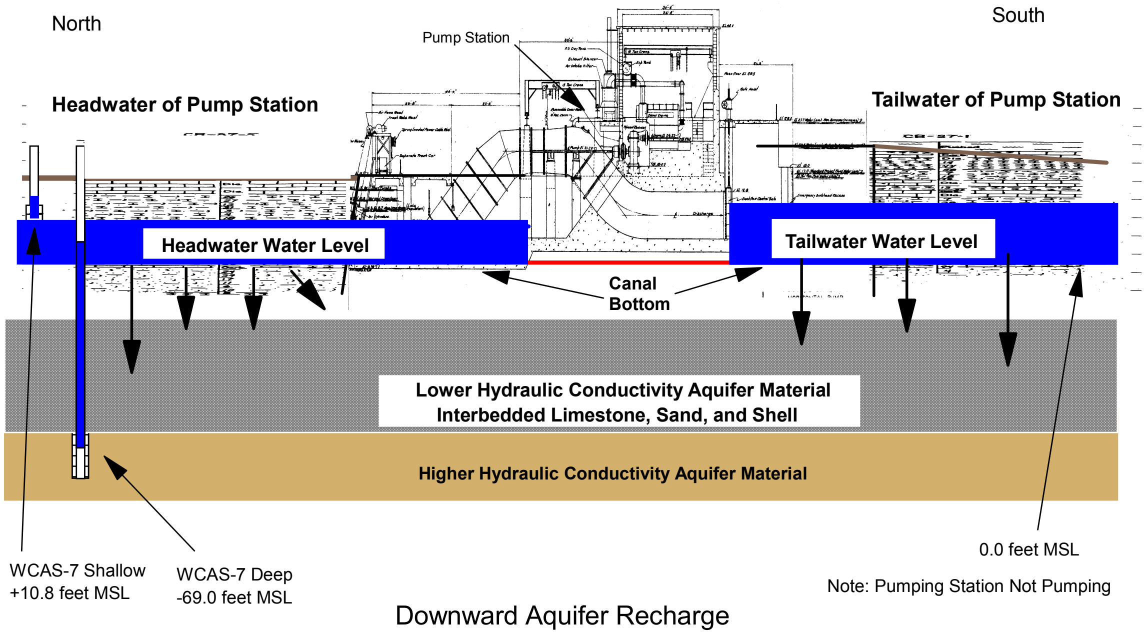


Figure B-5. S-7 Pump Station Field Investigation Graphical Cross-Section for Groundwater Flow Paths (Downward Aquifer Recharge)

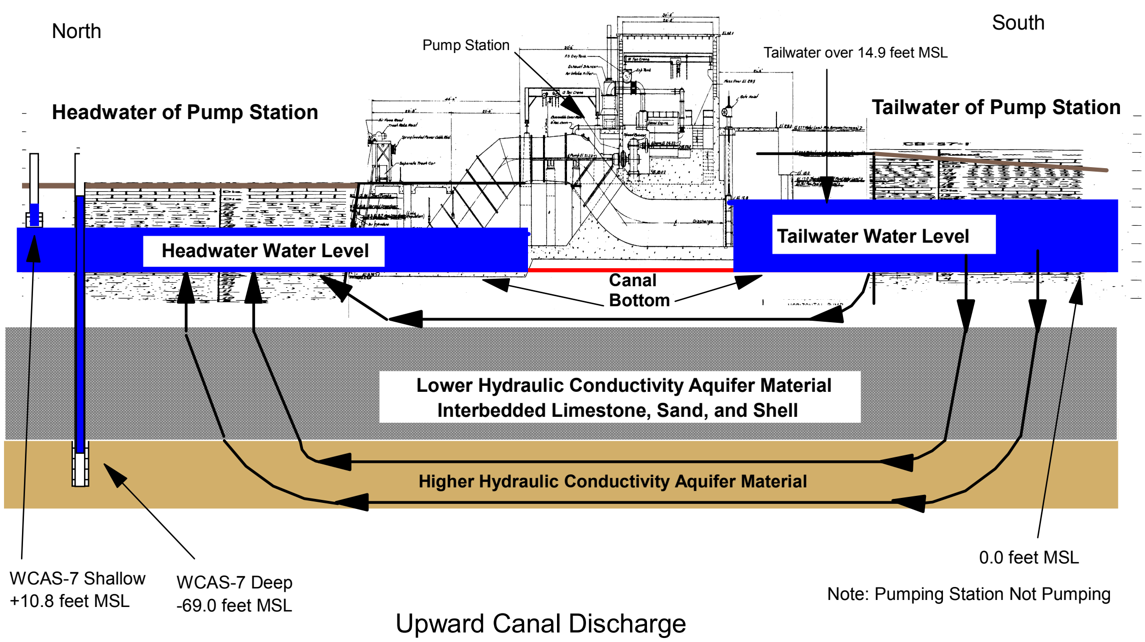
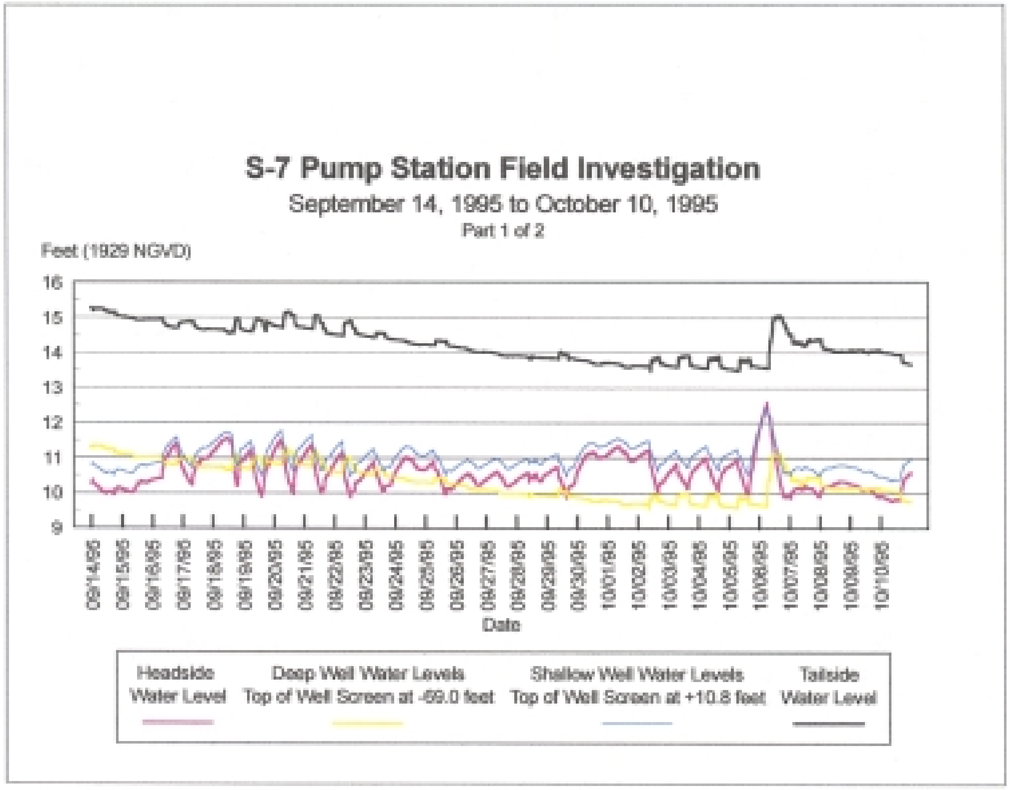


Figure B-6. S-7 Pump Station Field Investigation Graphical Cross-Section for Groundwater Flow Paths (Upward Canal Discharge)

APPENDIX C

S-7 PUMP STATION FIELD INVESTIGATION DATA

The 18 graphs provided in this appendix (**Figures C-1** through **C-9**) depict the water levels of the DO concentrations and the SC during the S-7 Pump Station field investigation.



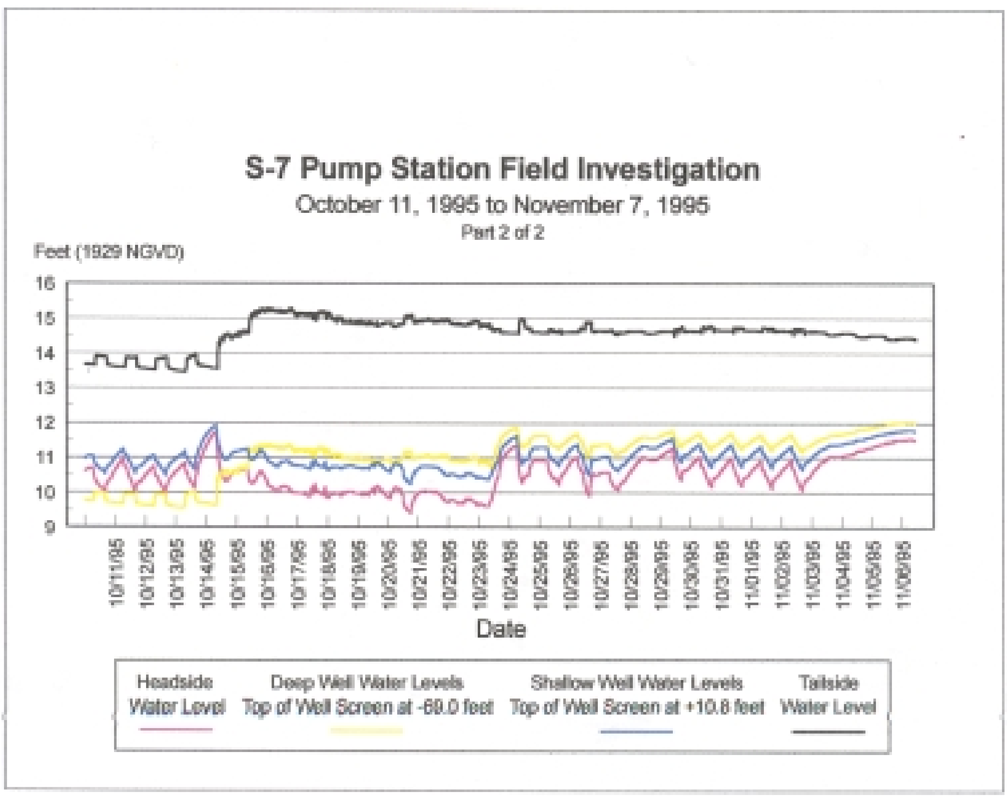
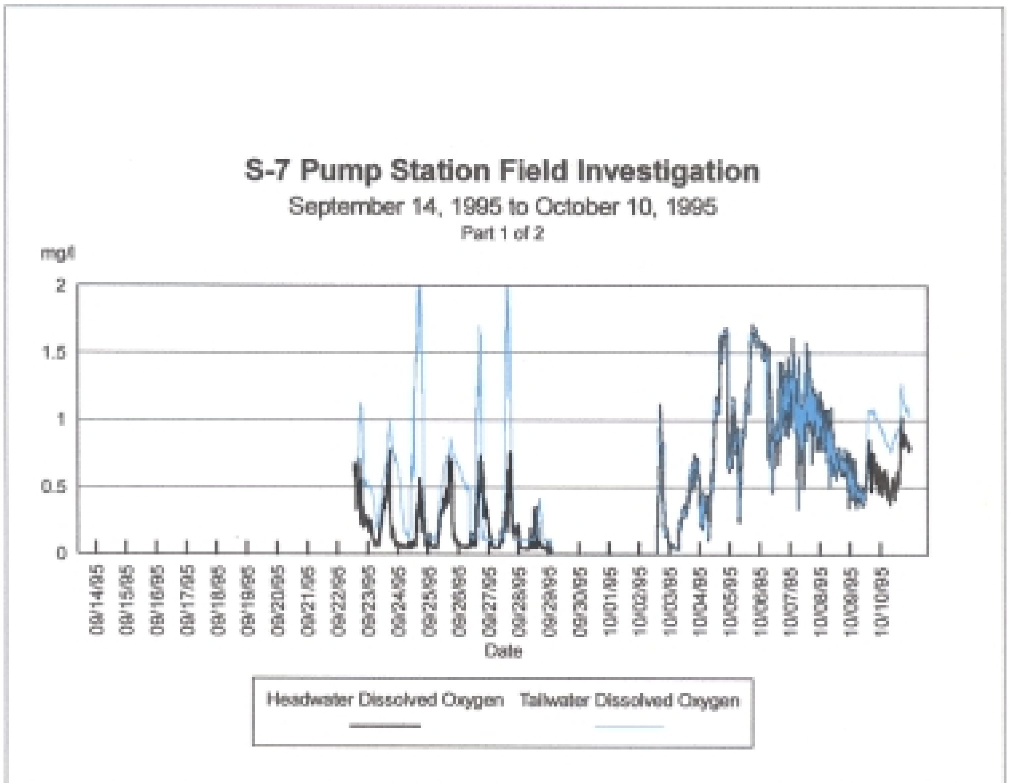


Figure C-1. Water Levels during the S-7 Pump Station Field Investigation



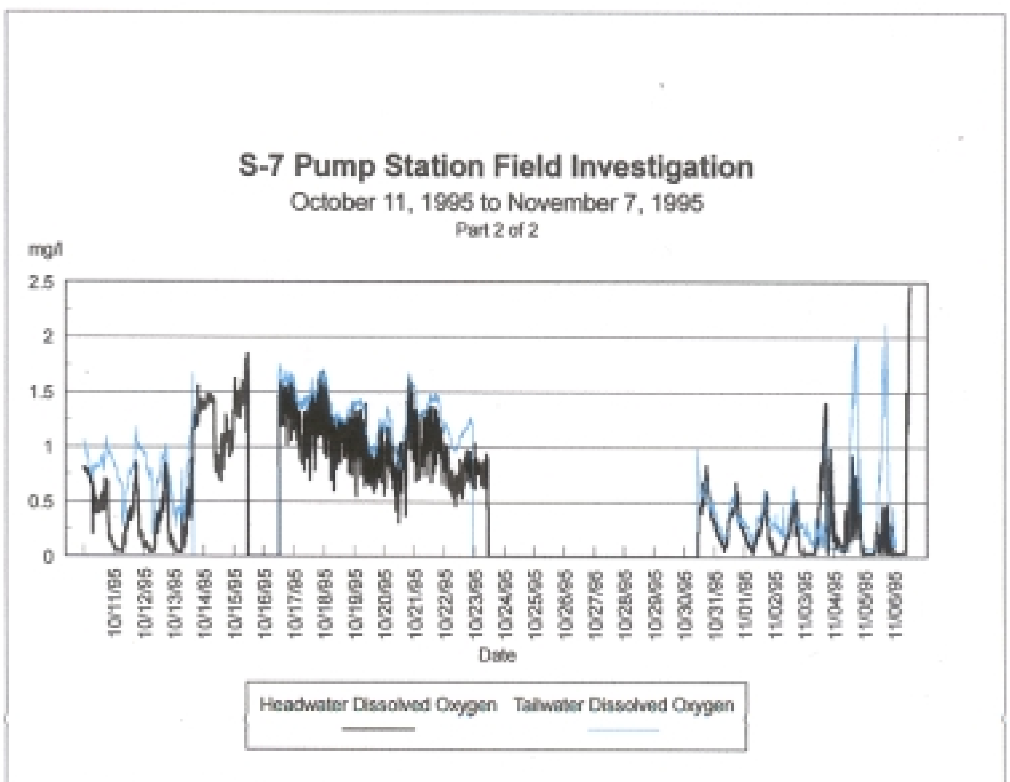
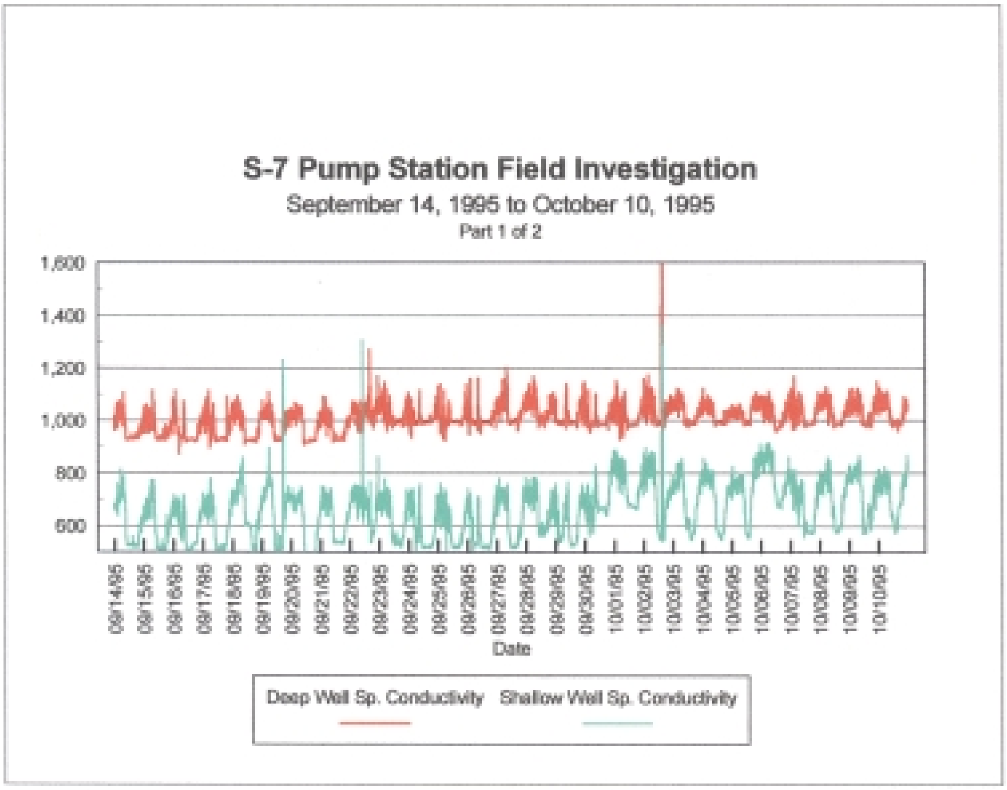


Figure C-2. Headwater and Tailwater Dissolved Oxygen during the S-7 Pump Station Field Investigation



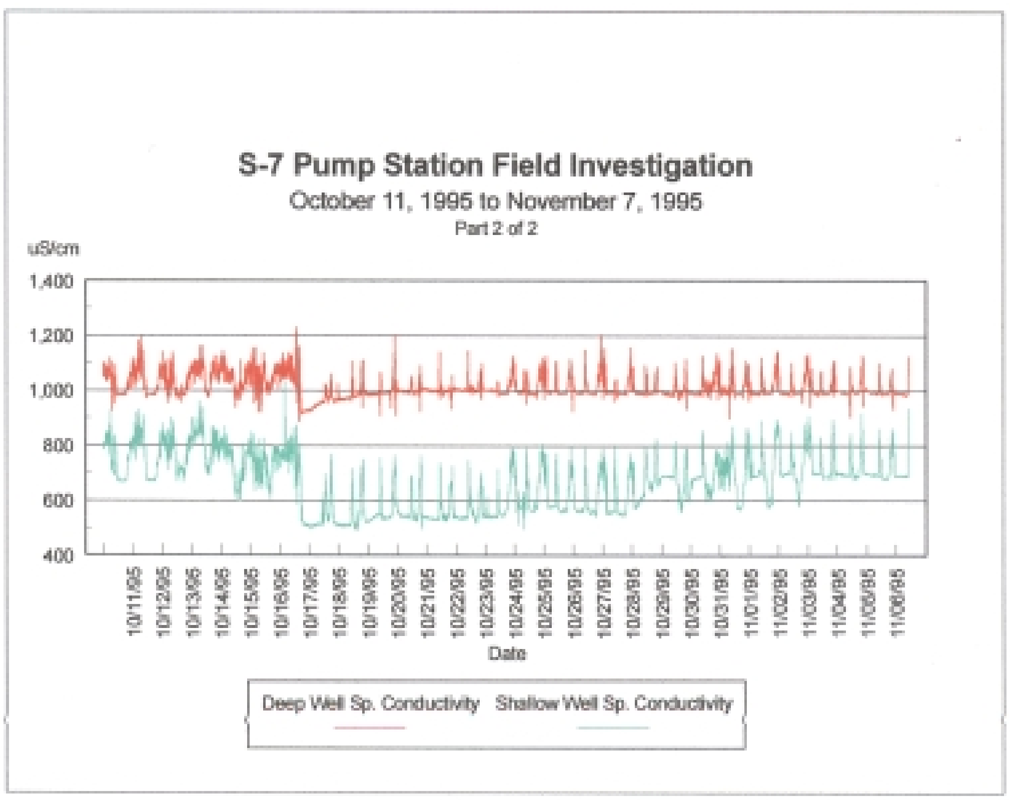
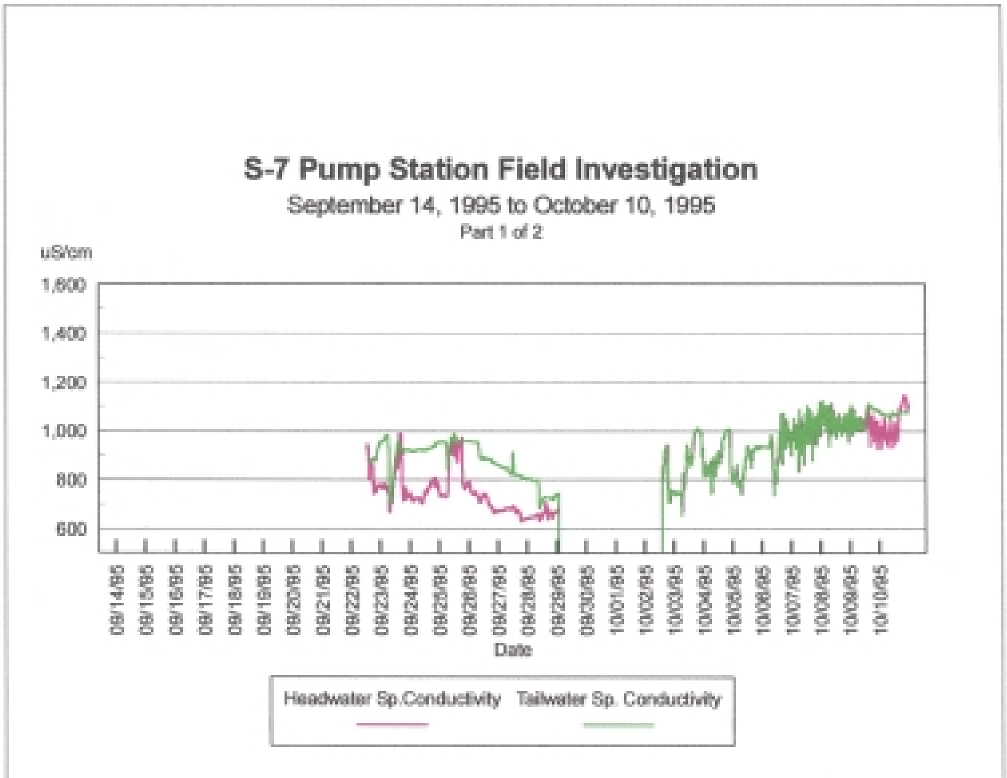


Figure C-3. Deep and Shallow Well Specific Conductivity during the S-7 Pump Station Field Investigation



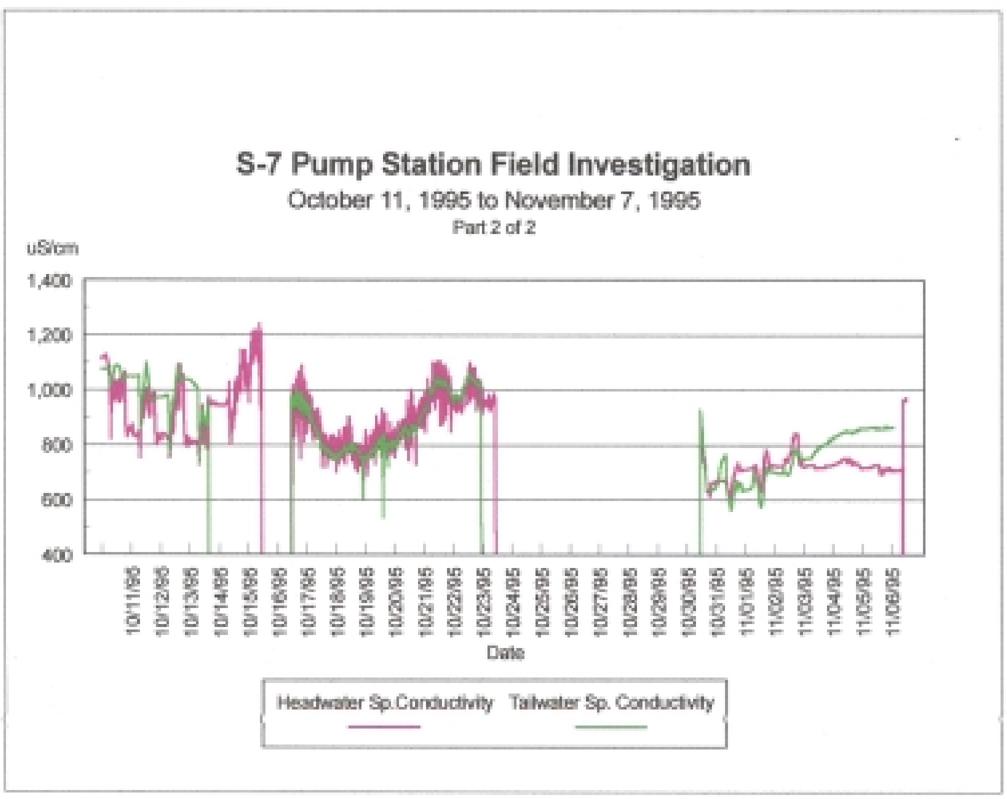
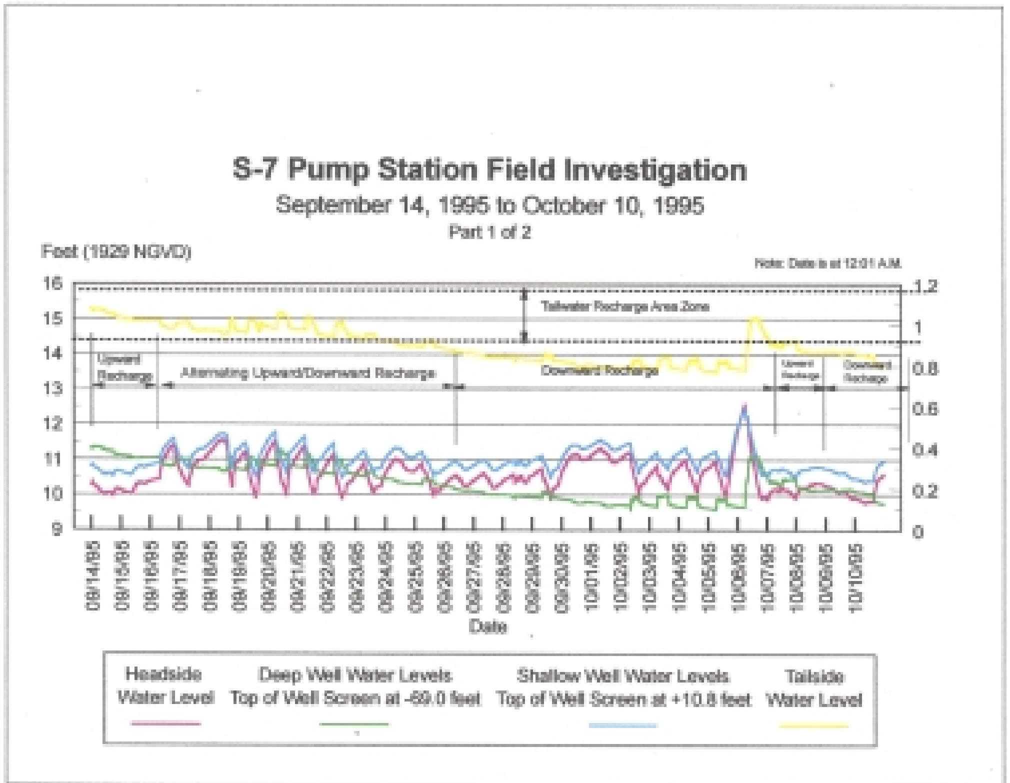


Figure C-4. Headwater and Tailwater Specific Conductivity during the S-7 Pump Station Field Investigation



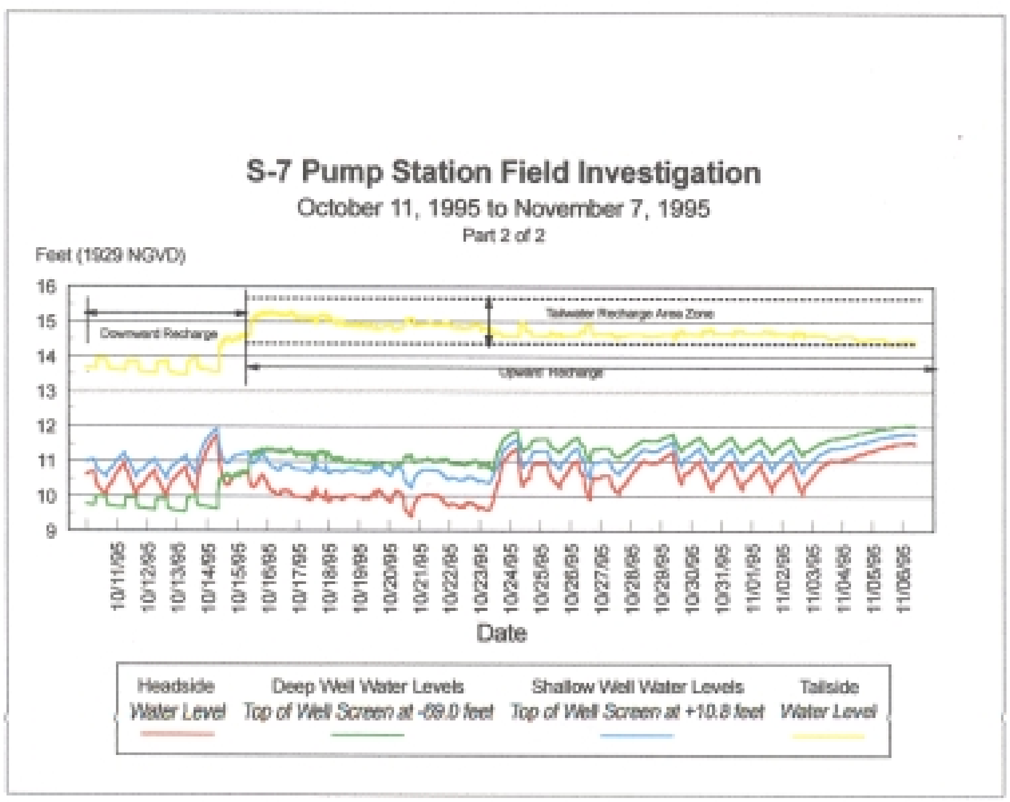
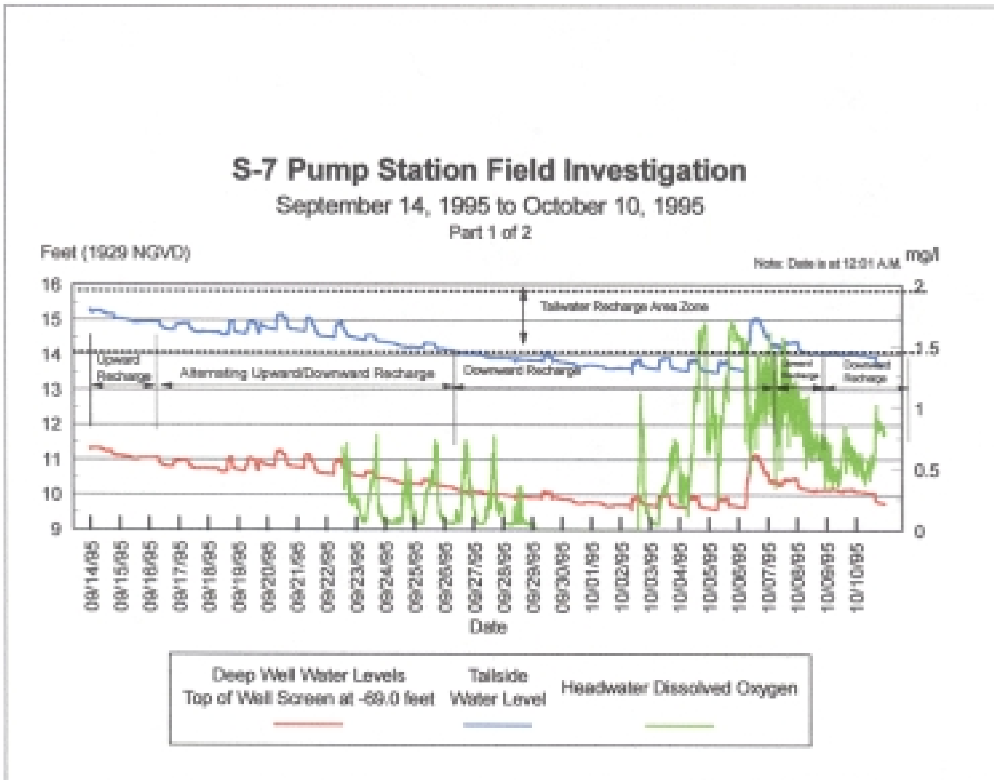


Figure C-5. Water Levels and Recharge during the S-7 Pump Station Field Investigation



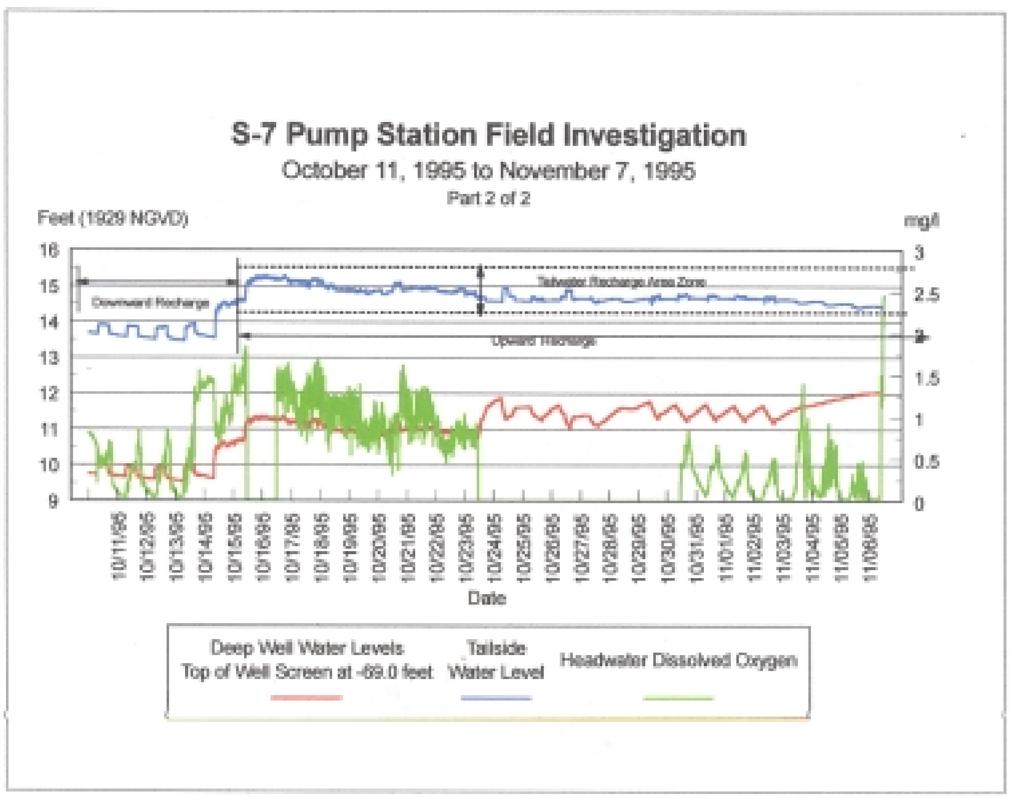
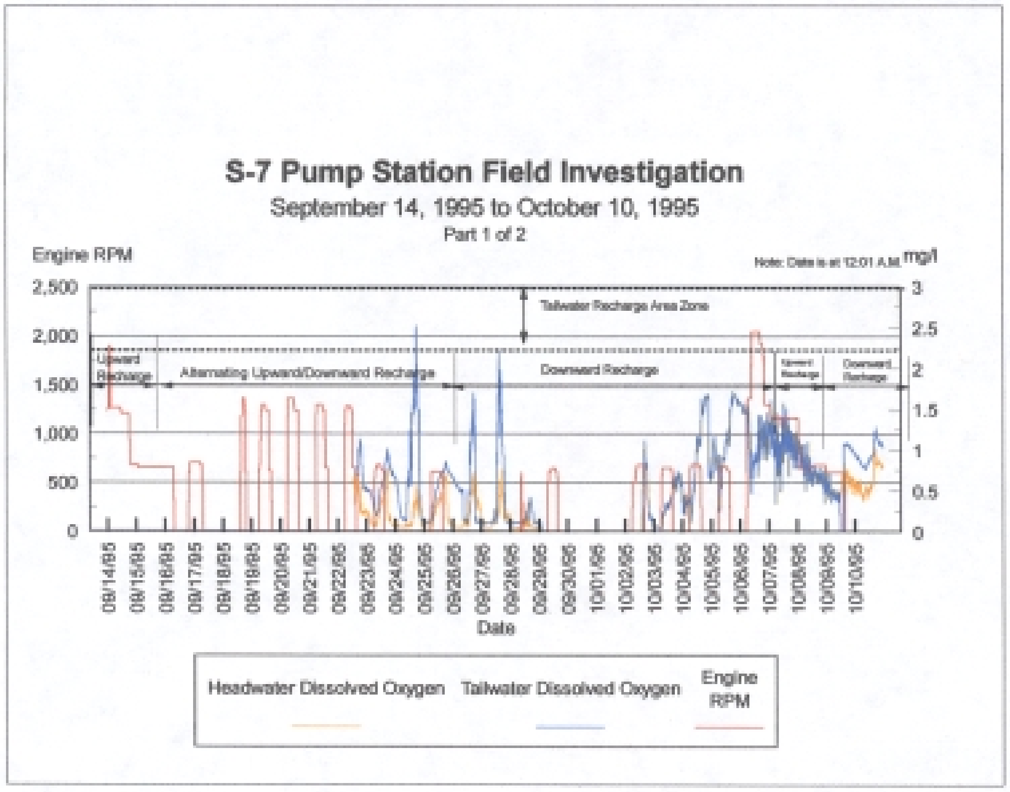


Figure C-6. Deep Well and Tailside Water Levels and Headwater Dissolved Oxygen during the S-7 Pump Station Field Investigation



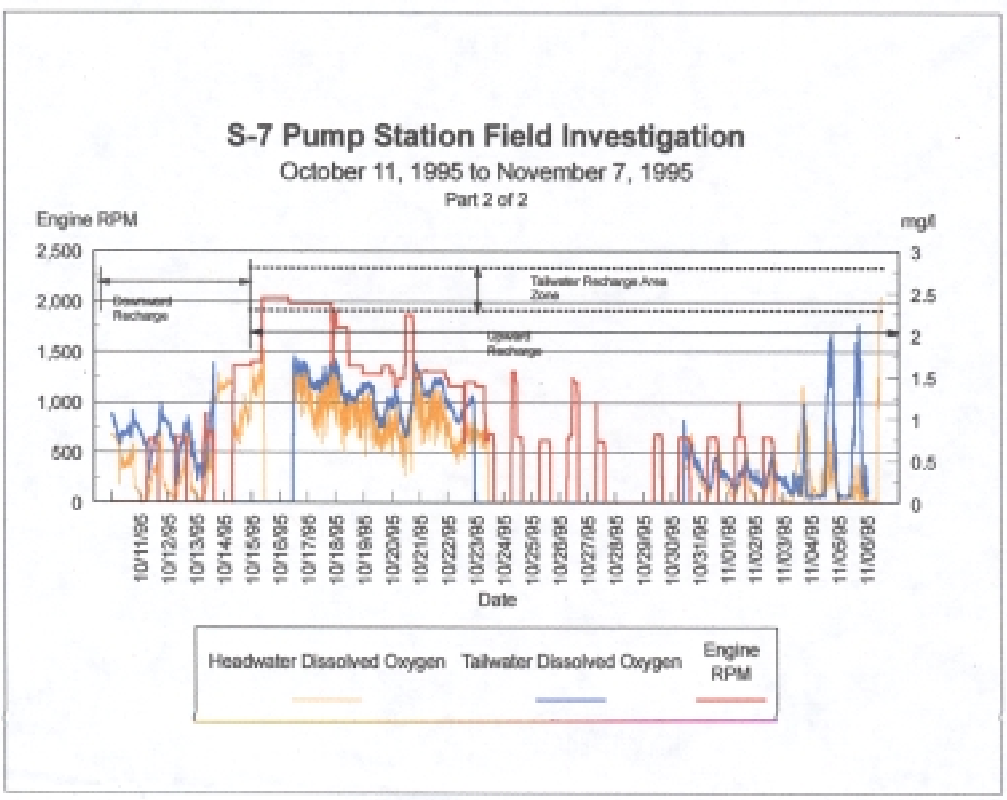
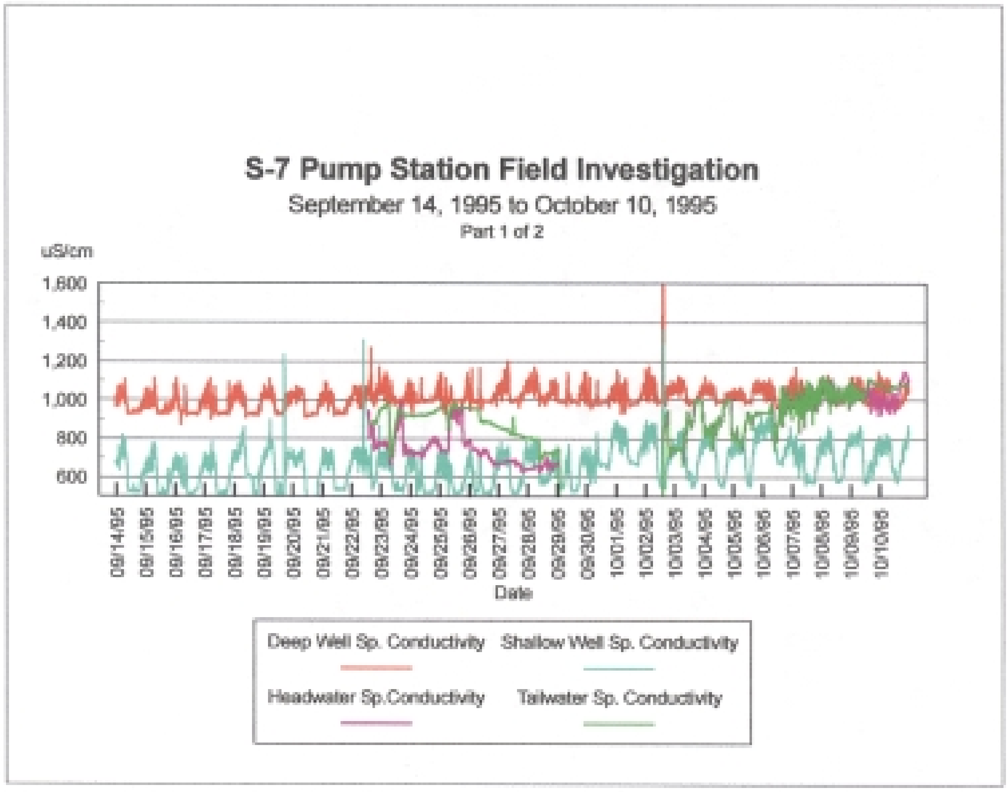


Figure C-7. Headwater and Tailwater Dissolved Oxygen and Engine Revolutions per Minute during the S-7 Pump Station Field Investigation



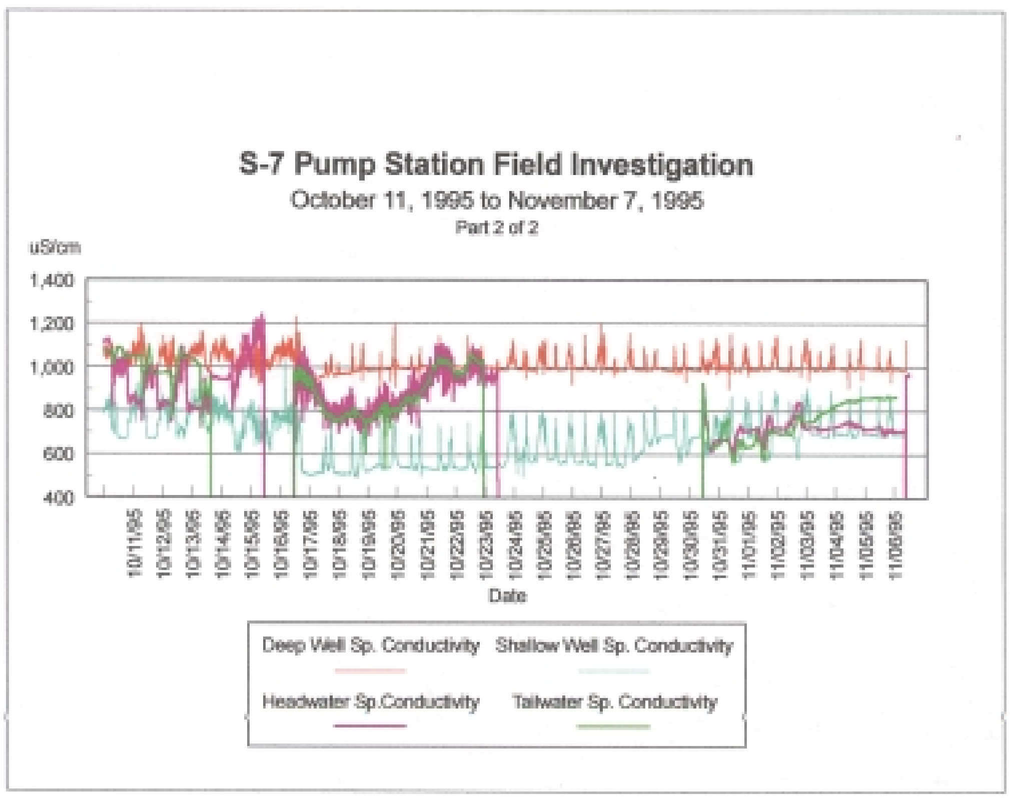
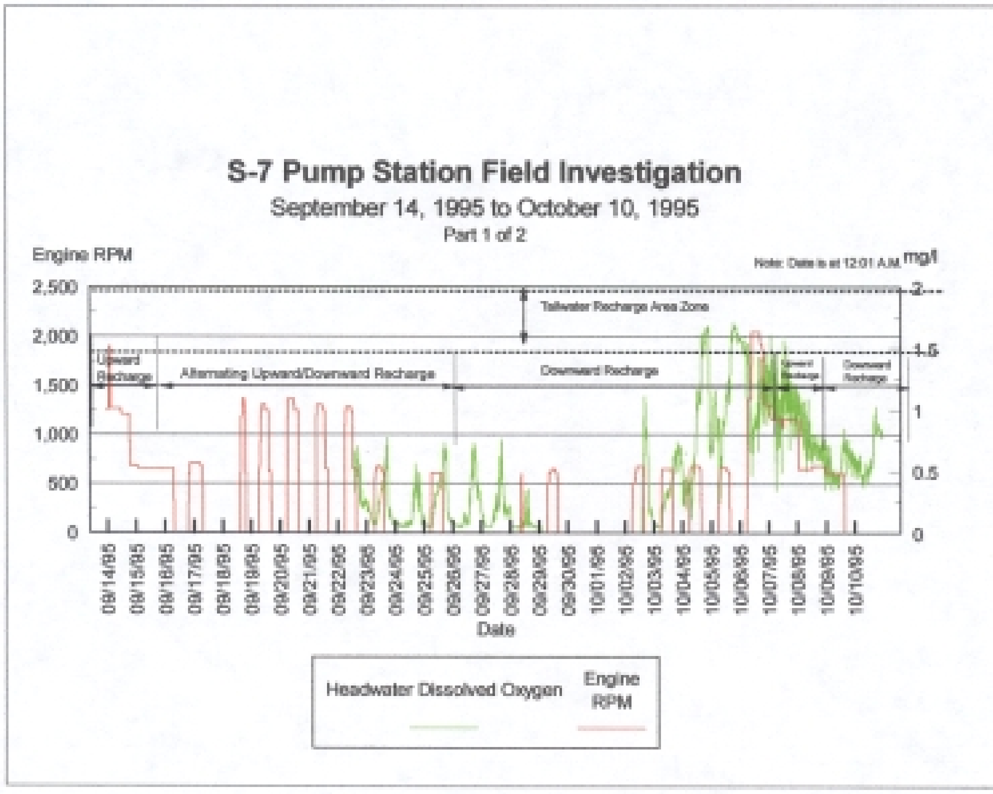


Figure C-8. Specific Conductivity during the S-7 Pump Station Field Investigation



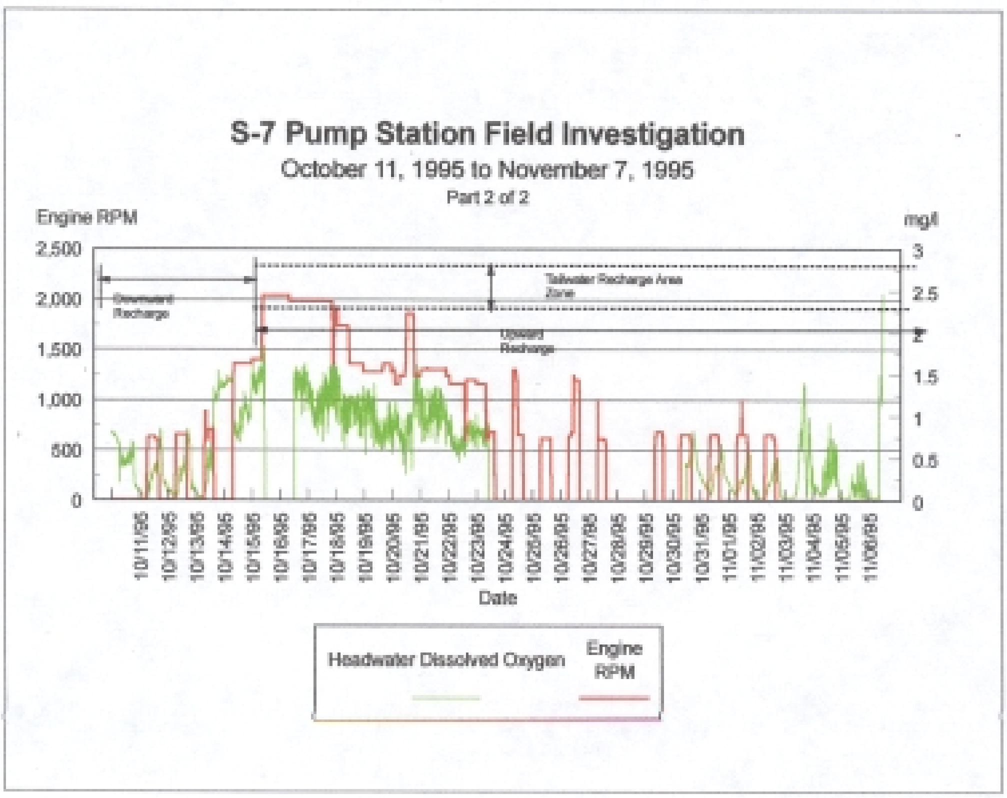


Figure C-9. Headwater Dissolved Oxygen and Engine Revolutions per Minute and Recharge during the S-7 Pump Station Field Investigation