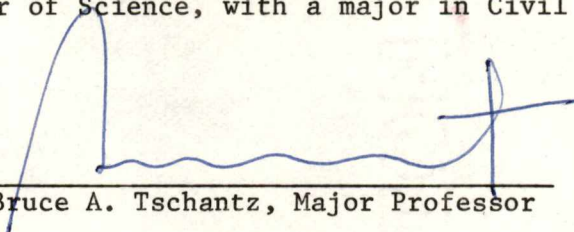


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AN ANALYSIS OF PIEZOMETER OBSERVATIONS FROM  
TVA'S TELlico DAM--MAIN EMBANKMENT

A Thesis  
Presented for the  
Master of Science  
Degree  
The University of Tennessee, Knoxville

James H. French

June 1986

To my wife,

Frances

## ACKNOWLEDGMENTS

Acknowledgment is given to the Tennessee Valley Authority for support on this project. Training and use of computing facilities was provided by TVA's Data Services Branch. In particular, acknowledgment is given to Jack D. Tuberville and Robert C. Beebe for encouraging and supporting the research. Acknowledgment is also given to TVA's Division of Engineering Design for providing project data for the analysis and initial guidance in formulating the scope of the research.

## ABSTRACT

The principal condition that is defended herein is that statistical methods can be used in conjunction with deterministic models to assist in analyzing monitoring data for dam safety. The context of this research is limited primarily to formulation and defense of data analysis methodology. Some conclusions regarding the performance of key structures are made on the basis of the data. The statistical methods used in this analysis involve modeling a relationship between the head recorded by piezometers and various time-averages of antecedent headwater and tailwater elevations. In addition to summary statistics, methods of correlation and regression are employed to describe this relationship. Steady-flow equations are used to formulate linear probabilistic models, and also provide the basis for flow net analyses.

The analysis is based on five years of monthly observations from 72 piezometers adjacent to the 2700 ft long, 105 ft high main embankment at Tellico Dam. The Tellico Project is a multipurpose project on the Little Tennessee River in Loudon County, Tennessee, built and operated by the Tennessee Valley Authority (TVA). The closure of Tellico dam occurred on November 29, 1979. The dam site is underlain by the Ordovician Sevier Shale, a diversified group of calcareous sedimentary rocks. A network of bedding planes, fault planes, joints, and fractures in the Sevier Formation aided in the development of karstic features noted in TVA geologic investigations. Because of the karstic nature of the

calcareous bedrock, TVA design staffs specified a grout curtain for the proposed dam. Major structural elements of the embankment design include a drainage system consisting of a vertical chimney drain, horizontal drainage blanket and toe drain, a grout curtain, a cutoff trench, and an upstream channel blanket. The foundation porewater pressure measuring devices are the source of data for this research, and consist of both the pneumatic diaphragm-type and open standpipe type. Five principal sections normal to the embankment baseline are monitored with pneumatic piezometers. In addition, a range of standpipe piezometers is aligned with the downstream toe of the embankment.

According to TVA engineers, the purpose of the main embankment piezometric instrumentation is to monitor the effectiveness of the cutoff trench and grout curtain and to monitor uplift pressures beneath the embankment. The pneumatic piezometers located in rock were specifically placed to monitor pressures in water bearing seams.

The subject piezometric data were placed on a computer database as part of a TVA pilot project to automate initial processing and archival of monitoring data. Piezometric data for the period June 1980 through February 1985 were provided by design engineers and consisted of monthly observations of hydraulic head computed from pressure readings and instrument elevations. Steady flow equations and Darcian assumptions are used to formulate regression models and construct flow nets. In order to establish causal relationships and to facilitate statistical analyses, a series of headwater/tailwater variables (referred to as HW/TW variables), representing time averages of reservoir elevations assumed

or estimated to exist prior to piezometer observation, were computed and added to the database. The HW/TW variables thus represent a simplification of time-fluctuations of reservoir elevations, created for comparison with recorded piezometric heads and for use in steady-flow equations.

For this research, data analysis was accomplished primarily on a microcomputer to minimize costs and provide greater flexibility. BASIC language programs were written as needed to analyze and report the data. The results were then spot-checked with statistical software available on the TVA mainframe computer. Results include summary statistics and plots, correlation, regression, and flow net analyses.

In general, results of the correlation analysis show strong correlation between the observed piezometric elevations and the various HW/TW variables. Correlation results are generally consistent with the locations of the piezometers within the respective sections. The results of the correlation analysis provide a basis for further investigation of the relationship between the HW/TW variables and the observed piezometric elevations. This is accomplished using regression.

An expression based on the modified Bernoulli equation and Darcy's law forms the basis for a multiple linear regression model applied to the piezometer data. This model is derived on the assumption of steady flow, but is modified to account for observed fluctuations in piezometric head. For this model, a piezometric head is modeled as a linear combination of headwater and tailwater variables. An alternative model based on the assumption of total seepage cutoff and hydrostatic

conditions utilizes only one predictor variable. Regression models for each case were determined for each individual piezometer and compared.

The results show that, in general, more variation in head is explained for the standpipe piezometers than for the pneumatic piezometers (92% vs 67% for the multiple linear models). On the average, the percent of explained variation (R-SQUARE) for the multiple linear models was only 2-3% greater than R-SQUARE for the simple linear models (67% vs 64% for pneumatic piezometers and 92% vs 90% for standpipe piezometers). In many cases, comparison of multiple and simple linear models indicates only modest improvement of performance indicators by addition of a second predictor variable. The inference to be made from these results is that flow is occurring through the foundation, but that this flow has been considerably reduced by the seepage control structures.

The results of the regression analysis were statistically significant, as shown by t tests on model regression coefficients. With a few exceptions, the single HW/TW predictor variables are significant at a minimum level of  $\alpha = 0.001$ . This implies that there is a greater than 99.9% probability that a relationship exists between the piezometric response and the respective HW/TW predictor variables selected. The 99% confidence interval for multiple regression models is on the order of  $\pm 3.9$  ft for pneumatic and  $\pm 1.6$  ft for standpipe piezometers.

A flow net analysis was conducted in order to enhance understanding and interpretation of regression analysis results by graphical depiction of piezometer location within the seepage field. Five flow nets based

on instrumented sections normal to the embankment baseline were constructed. The sections were considerably simplified in order to effect solutions. The technique employed involved first constructing equipotential contours onto each section utilizing the piezometric data and then fitting flow lines to these contours. The unit discharges computed for the sections analyzed ranged from a maximum of  $9.92\text{E-}3$  cfs to a minimum of  $2.33\text{E-}3$  cfs, and averaged  $7.35\text{E-}3$  cfs. Based on these results, the estimated total discharge (Q) underneath the embankment is  $Q = 20$  cfs. This represents 0.35% of the estimated mean annual streamflow at the site (5700 cfs). The total discharge estimate for foundation seepage (20 cfs) is considered reasonable in relation to the data analyzed and conditions at the project--however, it should only be considered an indication of the order of magnitude, owing to foundation heterogeneity. It is clear from the flow net models that the permeability of the grouted zone is the critical factor controlling discharge through the foundation. Flow net results seem to indicate a differential in the hydraulic conductivity of the foundation bedrock on either side of the grouted zone--layered heterogeneity of foundation bedrock is a possible explanation for this observation.

The research presented has implications for dam safety monitoring in general, in addition to implications regarding the Tellico project. An important potential application for the regression analysis presented is in the area of data validation and quality control. The regression models provide an expected range of head (or pressure), given antecedent headwater/tailwater conditions. The modeling has the potential for

systematic data validation checks, incorporable into computer algorithms. The purpose of the proposed validation checks is to improve data quality and detect data observations that differ significantly from past behavior. Immediate processing and evaluation is also a high priority. The applicability of linear regression modeling of the type presented herein to other projects is uncertain. Similar model performance would be expected in similar conditions, in a fractured, jointed, and/or karstic strata.

The modeling results have other specific implications for the Tellico project. The results indicate a significant reduction in flow potential by the grout curtain. Pressures close to hydrostatic are found under the downstream toe of the embankment, which is favorable from the standpoint of stability. The estimated total seepage under the embankment (20 cfs) does not represent a significant figure in terms of economic water losses.

The results obtained confirm that statistical methods, particularly regression, can be used to assist in analyzing monitoring data for dam safety. The regression model results were statistically significant and have possible applications in both initial validation and detailed evaluation of project data. If carefully planned and implemented, the methods presented can assist in monitoring for dam safety.

## PREFACE

The research on this topic began in 1984, coincident with an effort within TVA design and service organizations to develop and utilize computer methods for processing and analysis of monitoring data. During the time the research was conducted, the author was employed by TVA's Data Services Branch in a group that provides monitoring data reduction, validation, and other services for a lead group of design engineers.

In June 1984 a meeting was held with TVA design engineers and managers to discuss an initial research proposal. Those present included James H. Coulson, Harold C. Buttrey and David Tanner of TVA's Division of Engineering Design, Jack Tuberville of Data Services Branch, and the author. Topics discussed included the context of academic research involving the use of TVA data, as well as the proposed methods of investigation. The Tellico project was recommended for analysis over other projects where trends in the data were less established. Subsequent to this meeting, a final research proposal was drafted and agreed upon. Tellico project data for use in the research were provided by David Tanner and Carl Tockstein of TVA's Division of Engineering Design.

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PLATE

IN POCKET

1. Embankment Design
2. Excavation and Foundation Grouting
3. Details of Instrumentation

## LIST OF ABBREVIATIONS

|          |                                                              |
|----------|--------------------------------------------------------------|
| $\rho$   | = fluid density                                              |
| $\nu$    | = kinematic viscosity                                        |
| $\psi$   | = stream function                                            |
| $\gamma$ | = unit weight of fluid                                       |
| $\phi$   | = velocity potential function                                |
| A        | = regression constant estimate                               |
| B        | = regression coefficient estimate                            |
| D        | = mean soil particle diameter                                |
| H        | = total head lost in the system                              |
| I        | = projection of hydraulic gradient onto<br>the conduit plane |
| K        | = hydraulic conductivity                                     |
| P        | = pressure                                                   |
| S        | = standard error of estimate                                 |
| V        | = fluid velocity                                             |
| X        | = independent variable                                       |
| Y        | = dependent variable                                         |
| Z        | = elevation                                                  |
| a        | = regression constant                                        |
| b        | = regression coefficient                                     |
| d        | = distance between adjacent equipotential<br>lines           |
| e        | = error                                                      |

- $g$  = gravitational constant
- $h$  = hydraulic head
- $i$  = hydraulic gradient
- $q$  = flow per unit width
- $r$  = sample correlation coefficient
- $s$  = streamline direction
- $t$  = time
- $u$  = absolute (dynamic) viscosity
- $v$  = discharge velocity
- $Ke$  = energy dissipation factor
- $Nf$  = total number of flow channels
- $Nt$  = total number of equipotential drops
- $Pe$  = normalized flow potential
- $Re$  = soil Reynolds number
- $Ss$  = specific storage
- $HW$  = headwater elevation
- $TW$  = tailwater elevation
- $Yh$  = predicted  $Y$  value
- $hp$  = pressure head
- $v'$  = average velocity per unit width of a  
parallel plate conduit
- D.C. = degree of confidence
- R-SQUARE = sample coefficient of determination

## INTRODUCTION

The purpose of this research is to analyze post construction piezometric data from the main embankment at TVA's Tellico Project and to relate the results obtained to instrument and embankment performance. The principal condition that will be defended herein is that statistical methods can be used in conjunction with deterministic models to assist in analyzing monitoring data for dam safety.

This research attempts to contribute to an area of dam engineering identified by experts in the field as needing further study--the monitoring of dams for their continued safety. Accompanying a slowdown in construction of large hydroprojects by Federal agencies has been increased emphasis on the monitoring and maintenance of existing structures. However, recent budgetary constraints necessitate that data from the monitoring effort be collected and analyzed in a cost-effective manner. Most importantly, data must be rapidly evaluated and accurately interpreted by engineers with dam safety responsibilities in order to identify possible unsafe conditions in time for action to be taken. This research attempts to apply new and existing approaches to the analysis of such data, with due emphasis on both the time factor involved and the purpose for the monitoring.

Several questions exist with respect to the monitoring instrumentation at the Tellico project. What is the purpose and need for the instrumentation? What are the factors that influence the observations, and how can the data be used to detect potentially dangerous conditions? Are the data valid? How can the observed data be used to describe

performance of the instrumentation and the system designed? These questions apply generally to any conscientious monitoring effort and will be given due consideration in this text. However, the context of this research is limited primarily to formulation and defense of data analysis methodology. Some conclusions regarding the performance of key structures are made on the basis of the data. A comprehensive assessment of Tellico project safety is the responsibility of TVA design engineers and is clearly beyond the scope of this research. Conclusions drawn herein are the result of independent investigation and do not necessarily reflect official agency viewpoints regarding dam safety.

The statistical methods to be used in this analysis involve modeling a relationship between the head recorded by individual piezometers and various time-averages of antecedent headwater and tailwater elevations. In addition to summary statistics, methods of correlation and regression are employed to describe this relationship. Steady-flow equations are used to formulate linear probabilistic models, and also provide the basis for flow net analyses. Though statistical methods are used, the study is not one of risk-analysis--no attempt is made to quantify the probability of failure based on the data observed. This study concentrates on the developing models that explain observed data, providing (1) analytical tools for the dam safety community-at-large, and (2) site-specific results for TVA.

This paper is organized to present and analyze the Tellico piezometric data within the context of both the purpose for dam safety monitoring in general, as well as factors site-specific to the project.

An overview of Federal dam safety monitoring, with emphasis on Federal guidelines and monitoring responsibilities at TVA, is presented in Section I. Section II provides a description of the Tellico project, with emphasis on the subject piezometers adjacent to the main embankment. In Section III, a review of other research having a bearing on this study is presented. Section IV presents analytical procedures used and the results obtained for statistical and flow net analyses. The results and implications of the research are then discussed in Section V.

## I. A PERSPECTIVE ON MONITORING FOR DAM SAFETY

### I.1 The Need For Monitoring

As long as there are risks of failure for dams, there will be a need for dam safety monitoring. The consequences of past dam failures have demonstrated a need for greater understanding of the physical processes that govern dam and accompanying foundation behavior. Monitoring programs can increase knowledge of these processes if properly designed and utilized.

The perceived need for dam safety programs has historically been the greatest after a dam failure, when public outcry prompts political response in the form of funding for reviewing the safety of these dams. Much of the present emphasis on dam safety in the United States is due to a succession of dam failures and near-failures in the last 25 years. Jansen (20:17) cites the near failure of the Lower Van Norman Dam in southern California during the February 1971 earthquake as being instrumental in raising public concern. This incident demonstrated the importance of considering seismic criteria and principles of soil dynamics in dam design. The failure of the Teton Dam in Idaho during filling in 1976 drew national attention to the dam safety issue. Additionally, because the Teton Dam was built by a Federal agency (the U.S. Bureau of Reclamation), this failure caused an in-depth investigation and evaluation of the procedures used by Federal Agencies in the design, construction and operation of dams.

## I.2 Development of Federal Guidelines

The Interagency Committee on Dam Safety (ICODS), formed after the Teton Dam failure in 1976, has been instrumental in improving Federal dam safety. Failure of this dam, in particular, raised questions about the need for monitoring and evaluation of seepage phenomenon. Initially an ad hoc panel, the group formed an Interagency Committee in response to President Carter's memorandum of 1977. ICODS was charged with reviewing the procedures and criteria used by Federal agencies and providing recommendations for improving Federal dam safety (57:ii). Additionally, the presidential memorandum initiated an independent review comprised of experts from the private and academic sectors (56:iii). The combined efforts of ICODS, the Independent Review Panel, and the participating Federal agencies contributed to the publication "Federal Guidelines for Dam Safety" (56). The basic thrust of this document was to "encourage high safety standards in the practices and procedures Federal agencies use or those they regulate for dam site investigation, design, construction, operation and maintenance, and emergency preparedness" (56:7).

The Federal guidelines present general considerations for all aspects of dam design and operation, including geotechnics and instrumentation--two especially relevant topics to this research. Recognizing that dam engineering requires expert judgment as well as sound application of physical laws and mathematics, ICODS made it clear that no one document could completely address all the necessary decisions that must

be made in the course of the life of the dam. The considerations presented represent a consensus among experts in the field at the time of publication (June 1979). On October 4, 1979, President Carter directed the Federal Agencies with dam safety responsibilities to implement the Federal Guidelines. In many cases, the subject agencies were already using sound practices in the area of dam safety--in other cases, implementation of the Federal guidelines resulted in improved practices.

Three documents describe progress made by the TVA in implementing the Federal guidelines. The document "Early Progress to Implement the Federal Guidelines for Dam Safety and Recommendations to Improve Federal Dam Safety Programs," published by the Federal Emergency Management Agency (FEMA) in July 1980 documented early progress and problems by all eight agencies in implementing the Federal guidelines (10). TVA progress in implementing the Federal guidelines over the period January 1980 to October 1981 was presented in the 1984 FEMA document "Biennial Progress Report on Implementation of Federal Guidelines for Dam Safety" (11). In December 1983, TVA published "Implementation for Federal Guidelines for Dam Safety," a progress report to FEMA covering the period October 1981 to September 1983 (48).

### I.3 A Definition of the Purpose for Foundation Monitoring

According to the Federal guidelines, foundation instrumentation is designed to (1) provide data for validating design assumptions, (2) provide information on the continuing behavior of the foundation through

time, (3) observe the performance of critical features, and (4) advance the state of the art in foundation engineering (18:22). The purpose of this research is therefore closely tied to the preceding definition of the purpose for monitoring--the results obtained should attempt to help satisfy these important objectives. Also important is an understanding of what monitoring cannot do--the Federal guidelines stress that monitoring alone cannot certify the safety of the foundation (18:22).

#### I.4 The Framework for Dam Safety Monitoring Within TVA

The Tennessee Valley Authority has considerable experience and expertise in the field of dam engineering. As pointed out by the agency in "Implementation of Federal Guidelines," TVA has complete responsibility for all phases of dam engineering (planning, design, construction and operation) and constructs dams with its own forces (48:1). At this time, TVA has no plans to construct new dams and is presently examining safety issues at all of its existing dams. Since the beginning of the agency, TVA has utilized outside consultants to review design and construction activities for its major dams (10).

In accordance with the Federal guidelines, TVA has identified and documented organizational responsibilities for dam safety. Of interest are the groups within TVA that participate in the monitoring effort at the Tellico project. The Hydro Design Projects group (HDP), within TVA's Division of Engineering Design (EN DES) is designated the lead group within TVA for project safety. As such, HDP has general

responsibility for dam safety monitoring within TVA. Under the direction of HDP, the Data Services Branch (DSB) coordinates transmittal of dam safety monitoring data for selected projects from field personnel and process the data for use by HDP. Data tabulation, reduction, initial validation, plotting, and field note archival are among the services provided by DSB to HDP. Field operations personnel include engineers and technicians trained in making routine on-site observations and inspections.

As part of the process of implementing Federal guidelines, TVA has implemented and documented a system of site inspections for dam safety. Four types of inspections varying from formal inspection of structural elements by specialists to informal inspections of dam safety-related features by operating personnel are conducted at regular intervals and additionally as necessary. As stated in "Implementation of Federal Guidelines," these inspections are intended to "disclose conditions which might threaten dam safety or disrupt operation in time for them to be corrected" (9:A3-1). The on-site inspection of visible features, along with monitoring, is a necessary component of a dam safety program.

## II. DESCRIPTION OF THE TELLICO PROJECT

### II.1 General Description

The Tellico Project is a multipurpose project on the Little Tennessee River in Loudon County, Tennessee, built and operated by TVA. Figure 1 shows the general project location. A general plan and section of the main embankment is shown in Figure 2. The main dam consists of a concrete gravity nonoverflow dam with 126,000 cfs spillway capacity and a 2700 ft long earth embankment (45:1). The main dam is one air mile southeast of Lenoir City, Tennessee, at mile 0.3 on the Little Tennessee River. The mean unregulated streamflow at the site (period of record 1921-1967) is 5700 cfs (45:1). TVA's multipurpose Fort Loudon Dam is located on the Tennessee River approximately one mile upstream from the confluence with the Little Tennessee River. Other principal features of the project are a 1000 ft long canal joining Tellico Reservoir with Fort Loudon Lake and three saddle dams on the left rim. Tailwater conditions for the main dam are regulated by the surface of Watts Bar Reservoir on the Tennessee River. According to TVA project data, the main dam creates a maximum static head of 80 ft and provides an estimated 200 million kwh of energy annually through the Fort Loudon Dam turbines by adding flow into Fort Loudon reservoir through the canal (45:2). A thirty-mile navigable channel (9 ft minimum depth) extends up Tellico Reservoir along the Little Tennessee River and the reservoir provides 126,000 ac-ft of controlled flood storage (45:2). In addition to flood-control, power, and navigation, the Tellico Project provides

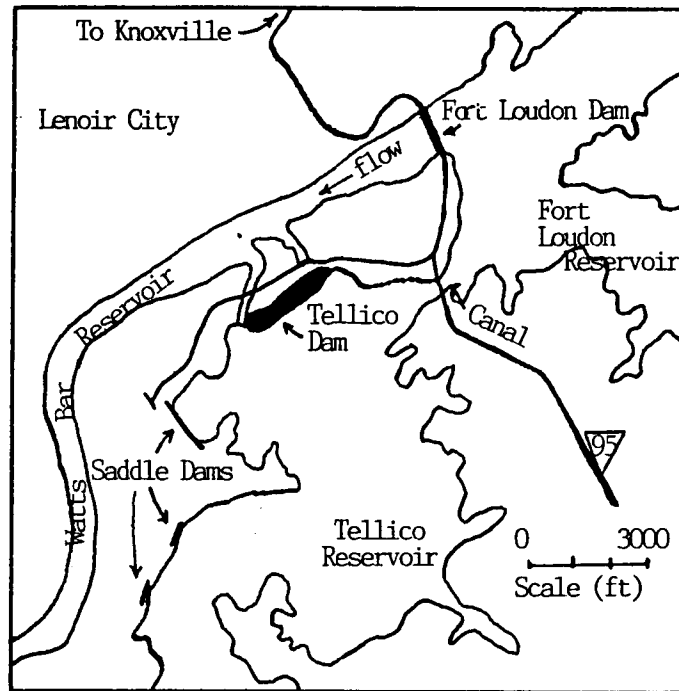


FIGURE 1. TELLICO PROJECT GENERAL LOCATION

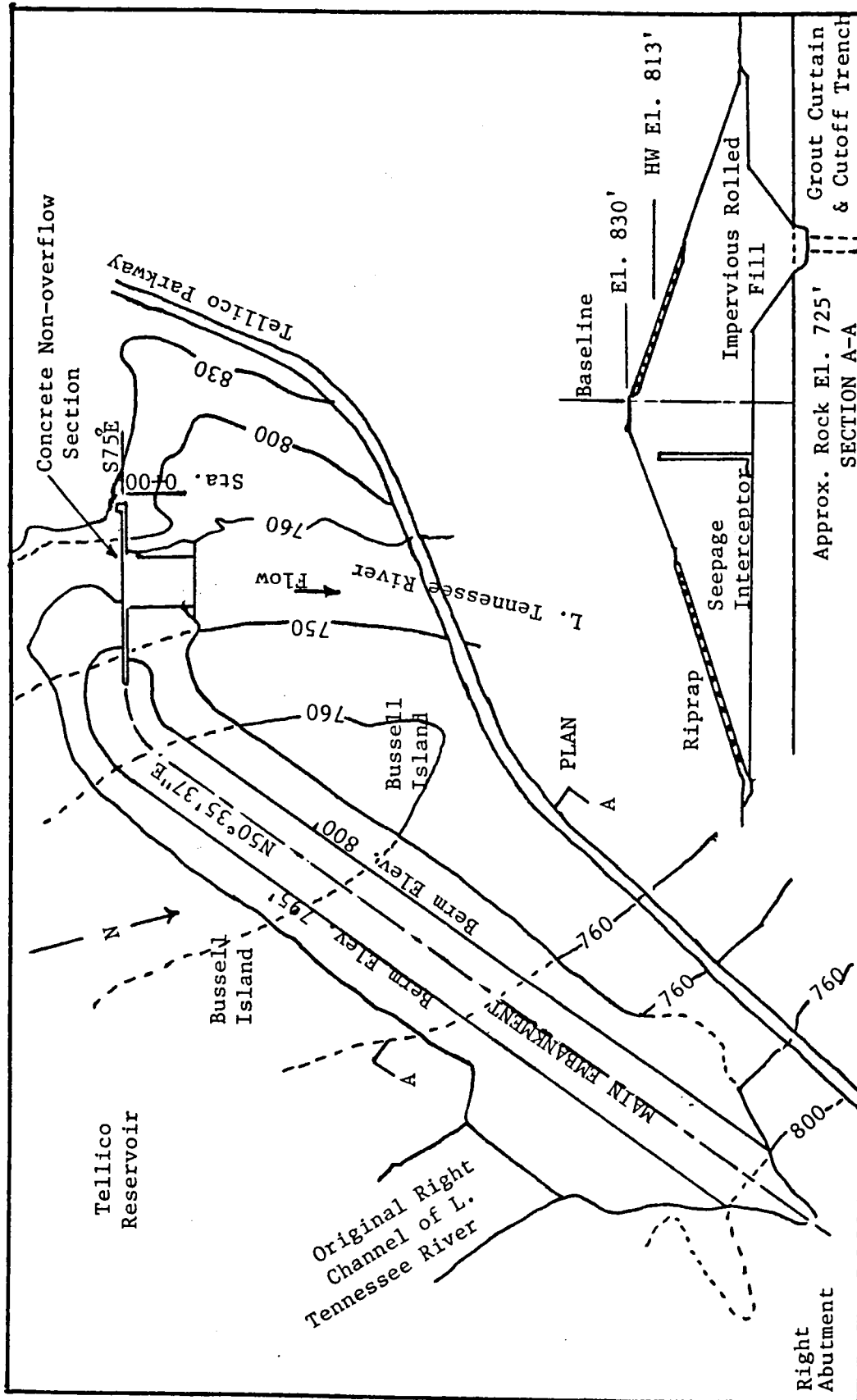


FIGURE 2. SIMPLIFIED GENERAL PLAN AND SECTION--MAIN EMBANKMENT

benefits through recreation, redevelopment, and shoreline development (39:1).

## II.2 Chronology of Activities

The closure of Tellico dam on November 29, 1979, occurred over 36 years after the preparation of plans for a dam on the Little Tennessee River. A dam on this river was first studied in connection with the Fort Loudon Dam, which was closed in 1943 (36:1). Soils exploration and laboratory testing for these initial plans occurred in 1943 (42.1:5). After deferral of these early plans, planning for the project resumed in the 1960s.

Since the appropriation of funds for the Tellico Project by Congress on October 15, 1966, the design and construction of the Tellico Project was a continuing process subject to the independent review of outside consultants. TVA submitted a total of 11 reports for consultants over the period 1966-1976, detailing design plans and construction activities (42). The consultants responded to these reports in writing and at periodic meetings with suggestions and considerations for TVA. Dr. Ralph B. Peck, Dr. James Sherard, and the late Dr. Frank A. Mitchell were among the experts who served on this board of consultants.

Funding problems and environmental questions delayed the construction and closure of the Tellico Project. Construction at the dam site started in March 1967 but was suspended in February 1969 because of a lack of funds and environmental litigation. Construction at the main dam resumed in 1973 (36:1). Fill placement for the main embankment and

saddle dams was completed in the fall of 1976 (42.10:1). At this time, installation of the embankment foundation instrumentation was well advanced, and plans were to start reservoir filling on about January 1, 1977 (42.10:4). Observations of the foundation instrumentation began in October, 1976. Before reservoir filling could be accomplished, the planned closure date was delayed by further environmental litigation. In 1979, Congress directed TVA to begin reservoir filling, and closure was effected on November 29, 1979.

### II.3 Site Geology

Geology is an important factor in assessing the suitability of a given site. Regional geology, geomorphology, structural geology, mineralogy, and seismology are among the subdisciplines of geology that must be considered in site selection and design. The importance of geology in dam engineering is put into perspective by the Teton Dam Failure of 1976. In a Congressional hearing in 1976 (57:5), Dr. Robert Curry, a specialist in hazard geology, pointed out that

The fundamental lesson to be learned from this tragedy is that better geologic information must be available prior to site selection . . . and, that far better procedural methods must be developed for continued review of technical site information as it is developed during preconstruction and construction phases.

The geology of the Tellico dam site plays an important part in the location of the dam, the procedures used to treat the foundation, and the type and location of monitoring instrumentation. The geology and foundation treatment of the Tellico Dam foundation was studied by TVA

from the start of initial plans in 1943 to closure, and the findings are summarized in the 1982 document "Final Geologic and Foundation Treatment" (46). Virtually all the material in this document was presented in the 11 reports "Information for Consultants" (42.1-11) for outside review during the design and construction process.

### II.3.1 General Geology

The Tellico Dam lies within the Ridge and Valley geomorphic province within the Appalachian Highlands. The province is characterized by roughly parallel ridges of sedimentary rock trending in northeast-southwest direction, coincident with the strike of strata. The region has been folded and faulted in response to tectonic activity, and the present topography in the vicinity of the dam site can be attributed to these features.

#### II.3.1.1 Foundation Bedrock

The Tellico Dam site is underlain by the Ordovician Sevier Shale, a diversified group of calcareous sedimentary rocks. According to TVA geologists, the Sevier Formation consists of at least ten distinct members, ranging in carbonate content from pure coarsely crystalline limestones to bluish-grey calcareous shales (42.1:A1-1).

TVA geologists divided the Sevier Formation into three units based on predominant lithology. Their descriptions of the lithology of these three units, found in "Final Foundation and Geologic Treatment" (46:5), are quoted for accuracy:

Unit 1--The lowermost 225 feet consists predominantly of limestones, which range from grayish, fine-grained impure limestones to gray and light-pink, fine to coarsely crystalline fossiliferous limestones with thin laminae of shale.

Unit 2--The next 325 feet consists of irregularly interbedded limestone and shale in nearly equal proportions. Wavy shale laminations are numerous and give the rock a somewhat nodular appearance. Bedding planes are indistinct. Although in some beds the argillaceous material is so abundant that the rock is essentially a calcareous shale, the unit as a whole is predominantly shaly limestone. A few thin beds of bluish-gray, fossiliferous limestones are mixed with the shaly limestones.

Unit 3--The upper 1,100 feet of the formation consists mostly of gray, calcareous shale with some interbedded limestone members. The thickest zone of interbedded shaly limestone, near the middle of the unit, is approximately 100 feet thick; but in most places such zones do not exceed 20 feet in thickness. The shale is dark gray where fresh but weathers to yellow or buff.

The structural geology of the Sevier Formation at the dam site is influenced by the characteristic regional folding and faulting that occurred in the Ridge and Valley Province. At the dam site, the Sevier Formation strikes from N40°E to N50°E and dips to the southeast from 10° to 60° (46:6). According to TVA geologists, the principal structural features in rocks in the vicinity of the dam site are two intersecting sets of joints trending parallel and normal to the strike (42.1:A1-3). Additionally, Unit 1 is cut by numerous strike faults (displacement parallel to strike), and other random joints and cracks are present (42.1:A1-3). The Knoxville Fault, trending SW-NE, is located approximately 2 miles to the southeast of the main embankment. According to TVA geologists, thrusting of the more competent Cambrian Copper Ridge Dolomite over the Ordovician Moccasin and Sevier Formations caused these units to become highly fractured (46:6). This network of bedding

planes, fault planes, joints, and fractures in the Sevier Formation aided in the development of karstic features noted in geologic investigations. During exploration and construction, numerous cavities were encountered. According to TVA geologists, carbonate material has been leached from the calcareous shales found in the Sevier Formation near the dam, leaving hydrated clays--this clay has filled many of the solution cavities encountered (46:7).

Because of the karstic nature of the calcareous bedrock, TVA design staffs specified a grout curtain for the proposed dam. Agency experience with dams founded on similar rock showed that high amounts of leakage could occur through an untreated foundation of this type.

Three sites were originally considered for the main dam. The present site, though it was the longest of the three layouts, was judged the most economical because less foundation treatment was required (46:8). The alternatives consisted of three layouts rotated about a common point on the left abutment (baseline station 0+00, Figure 2, p. 11). The decision to locate the dam at the present site was reached on the basis of the results of exploratory core drilling and prior experience with the construction of Fort Loudon Dam on the same formations (46:8). The present layout is founded entirely on Unit 2 of the Sevier formation.

A considerable amount of detailed geological information was collected during the exploration and construction phases of the project. During the period 1937-1944 and 1960-1977, 465 core holes averaging over 100 ft were drilled in the process of exploration, grouting, and

instrumentation installation (46:T8). Further reference will be made to this information as applicable.

#### II.4 Foundation Soils

The soils located at the dam site were the focus of two TVA investigations reported in 1943 and 1967.

Surficial soils ranging from highly pervious alluvial gravels to less permeable residual clays are present at the dam site. Soil horizons vary depending on geomorphic location--the soils of Bussell Island (Figure 2) are alluvial in nature while those of the right (NE) rim include residual clays and terrace gravels. The portion of the main embankment overlying the original right channel of the Little Tennessee River is founded directly on bedrock. A generalized section of the two major soil profiles is presented in Figure 3. The initial soils investigation showed that the proposed embankment soils showed good strength and that the pervious nature of the basal gravel deposits required treatment (42.1:5). Information from the 1943 investigation was used as preliminary material for the more detailed expanded soils investigation of the 1960s.

##### II.4.1 Soils of Bussell Island

The soils of Bussell Island are alluvial in nature and include three major continuous units. Directly overlying bedrock are discontinuous deposits of blended boulders and cobbles, followed by a continuous, well-rounded, sandy, silty gravel ranging in thickness from 4 to 10 ft

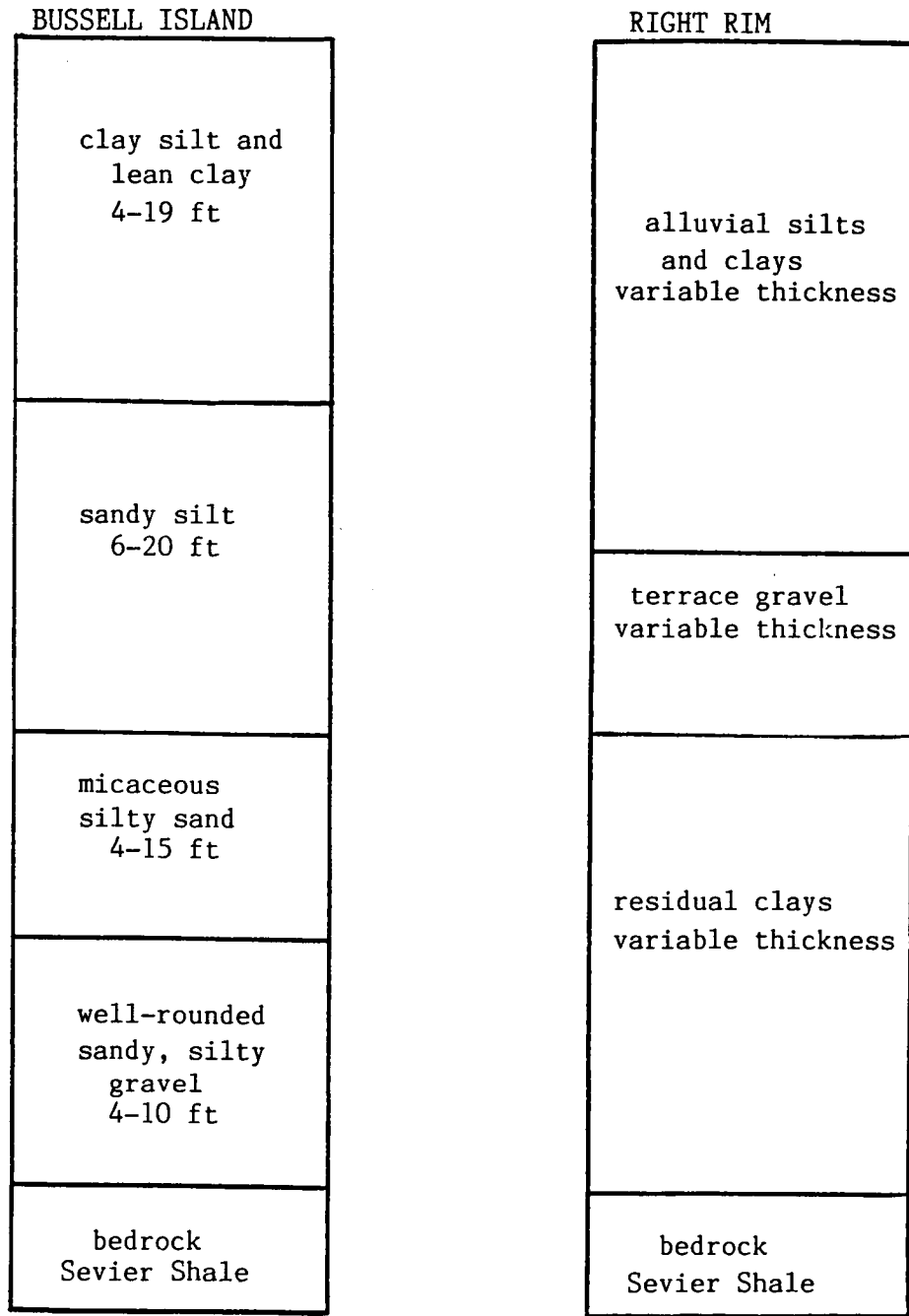


FIGURE 3. SIMPLIFIED EMBANKMENT FOUNDATION SOIL PROFILES

(44:2). Two pump tests made in this unit on the left and right side of Bussell Island in the 1940s gave permeability coefficients of 20,000 and 140,000 ft/day (0.016 and 0.11 cm/s) respectively (42.2:3). Overlying the gravel is a continuous layer of micaceous silty sand from 4 to 20 ft thick (44:2). Overlying the sand is 6 to 20 ft of sandy silt--this silt grades into an additional thickness of 4 to 19 ft of surficial clay, silt, and lean clay (44:2).

#### II.4.2 Soils of the Right Bank

Soils of the right bank grade from the alluvial flood plain deposits found on Bussell Island into colluvial and residual deposits. According to TVA soils investigators, these colluvial and residual deposits interfinger with the alluvium and are of variable thickness and lateral extent, thus comprising a relatively complex profile (44:2). The profile shown in Figure 3 shows a heavy clay residuum above bedrock, overlain by alluvial terrace gravels and surficial silts. Borings and Wenner electrical resistivity surveys indicated that the alluvial terrace gravel is discontinuous and ranges from pervious to semipervious in permeability, depending on the presence of fine particles (44:4).

#### II.4.3 Laboratory Testing

Laboratory test results are summarized in the TVA report "Tellico Dam Project-Soil Investigation and Laboratory Testing" (44). Representative samples were tested for their respective permeabilities, determined by the constant and falling head methods. The results of these

tests are presented in Appendix Table A-1. According to TVA investigators, the upper silty sands found in both of the major profiles were found to have permeabilities in the approximate range of  $10E-4$  to  $10E-6$  cm/s, while the nonplastic sands and gravels ranged in permeability from  $10E-4$  cm/s to "practically pervious" (free draining) (44:8).

Other tests included sieve analysis and Atterberg Limits, undrained (Q), consolidated (R), and drained (S) shear tests, unconfined compression, and consolidation (12:8). Results of consolidation testing showed the alluvial soils to be of low to medium compressibility and medium to highly preconsolidated (44:9).

#### II.5 Description of Embankment Design and Construction

The design plans for the main embankment, presented in Plate 1, were approved in May 1974. As previously stated, the design process involved a continuous dialogue between the TVA design staff and the outside consultants. A full account of design decisions and details is beyond the scope of this study--emphasis is placed on design criteria and information obtained during embankment construction relating to the monitoring program and the seepage regime.

Section A-A (Plate 1) shows the embankment to be founded directly on the 3 continuous alluvial strata characteristic of Bussell Island, and the truncation of these units by a cutoff trench. Major structural elements of the embankment design include a drainage system consisting of a vertical chimney drain, horizontal drainage blanket and toe drain, a grout curtain, a cutoff trench, and an upstream channel blanket.

The dam baseline, shown on Plate 1, is an important reference line. From baseline station 0+00 on the left abutment, the baseline trends S75°00'E. A 250 ft radius curve with P.C. at station 6+00 connects this first alignment with the major alignment of the dam at P.T. station 8+37.38. The major alignment of the baseline is N58°35'37"E. The embankment follows this alignment from the P.T. to station 34+00. Here, a cutoff trench extends further along the right abutment on a new alignment.

#### II.5.1 Foundation Treatment

A detailed account of foundation treatment procedures are given in the 1982 TVA report "Tellico Project--Final Geologic and Foundation Treatment" (46). Treatment included excavation of the cutoff trench, cleaning and mapping of the exposed bedrock surface and grouting. The additional information obtained from these activities included more detailed data on subsurface conditions, providing the basis for minor design modifications and design of the instrumentation program. The design blueprint for excavation and foundation grouting is shown in Plate 2. General criteria were provided on this drawing, allowing for special treatment of problems as encountered during construction.

##### II.5.1.1 Cutoff Trench

Excavation of the cutoff trench exposed several extensive areas of bad rock requiring special treatment. According to the TVA report, the development of solution cavities along structural features in the

bedrock necessitated rock excavation in the trench up to a depth of 50 ft (46:24). The alignment of the cutoff trench and grout curtain are shown on Plate 2 (Foundation Plan). The centerline (CL) of the cutoff trench and grout curtain starts near the dam baseline at the concrete non overflow section and trends eastward. Between stations 8+24.8 and 30+00, the trench assumes an alignment parallel to the baseline, 95 ft upstream. Of the cavities encountered, many were mud-filled. Exposed cavities were treated by cleaning to a depth equal to twice the width and backfilling with dental concrete (46:24). Rock faces with recesses were faced with concrete as was much of the trench bottom--according to the TVA report, this was done to enable compaction of the core material when placed and to form a surface for grouting activities (46:25).

Water in the cutoff trench was a problem during excavation and fill placement, and was observed flowing from various bedrock structural features. A dye test conducted to assess the connectivity of cavities gave interesting results--dye injected into a large cavity developed on a fault plane at station 24+15 emerged 40 minutes later in a cavity at station 20+72 (46:31). From this data, the average velocity of the dye is computed as 0.14 ft/s.

#### II.5.1.2 Cap Grouting

Cap grouting was utilized in several badly weathered areas of the cutoff trench. According to "Final Geologic and Foundation Treatment," this procedure typically consisted of lines of cap grout holes drilled 4 ft on centers 25 ft deep at 30° angles (46:39). This type of grouting

is usually utilized to provide a more firm foundation and reduce leakage.

#### II.5.1.3 Grout Curtain

Installation of the grout curtain was a procedure that varied with the conditions encountered in the cutoff trench. TVA design engineers specified that the curtain should effectively seal all seams in the rock to a minimum depth of 75 ft below the original rock surface. Grout curtains are generally used to treat erosive leakage, excessive uplift pressures, and high rates of leakage through structural features in bedrock.

According to the TVA report, several special treatment procedures were performed in a number of locations--these included installation of additional lines and grout pipes, redrilling, and changes in the basic grout formula (46:37). Criteria for the termination of grout in an individual hole was a 100-bag limit of cement--however, after reaching this limit, holes were redrilled and regouted until refusal was reached (46:40). Grout formula changes included the addition of calcium chloride to accelerate setting of grout within curtain limits and the addition of sand for use in outside lines and localized "high take" areas (46:37).

The minimum specifications for the curtain were 2 lines (rows) to a depth of 75 ft, aligned 5 ft upstream and downstream of the cutoff trench CL. The upstream line was typically installed first, and the holes were angled 30° from vertical in a plane parallel to the CL. The

upstream line was then installed similarly, but was angled 30° in the opposite direction. Because of badly weathered rock conditions, a third interior line aligned on the cutoff trench CL was installed between stations 19+55 and 30+00 (18:46). Grouting procedures are further detailed in the TVA report (46), which includes 57 plates showing curtain grouting along individual sections.

#### II.5.2 Embankment Fill

Placing of the fill for the main embankment followed excavation of the cutoff trench and grout curtain, starting at the concrete nonoverflow dam and proceeding toward the right bank. The main embankment was designed for a theoretical crest at elevation 830.0 ft, with up to a 2 ft overbuild to allow for settlement. The approximate vertical distance between the theoretical embankment crest and the preconstruction elevation of Bussell Island is 70 ft.

As shown on Plate 1 (Section A-A) the material specified for embankment fill is "impervious rolled fill." Exploration during earlier phases indicated that a sufficient amount of fill could be obtained from canal excavation and nearby borrow sites. Specifications for fill placed in the cutoff trench were based on gradation (maximum of 20% by weight over No. 40 sieve), moisture content (within 2% of optimum), and density (98% of standard proctor maximum) (43:22N205). For the remainder of the embankment, a minimum compaction of 95% of standard proctor maximum and gradation limit of 40% over the No. 40 sieve were specified (43:22N205).

Investigations of the fill material during construction included field control density and moisture tests on selected block samples as well as permeability and swelling tests on remolded and "undisturbed" samples (42.6:B-1). According to TVA investigators, permeability testing of block samples, remolded borrow samples and trimmed specimens from tube samples gave coefficients of permeability ranging from  $1.9\text{E-}6$  to  $3.8\text{E-}8$  cm/s, averaging  $4.7\text{E-}7$  cm/s for 8 tests (42.8:B-4).

Water was a problem during placement of the fill in the cutoff trench near the concrete section. The ingress of water resulted in unacceptably high moisture contents--fill in this section was excavated and concrete was instead placed in the bottom of the trench.

### II.5.3 Drainage System

Major elements of the drainage system shown in Plate 1 are a vertical chimney drain, horizontal drainage blanket, and toe drain. A well-graded filter sand was used for the chimney and blanket drains. Specifications called for a maximum of 5% of the material by weight to be coarser than the No. 100 sieve and 2% of the material to be coarser than the No. 200 sieve when subjected to wet sieve analysis (43:22N205). The filter sand was tested for gradation, relative density, and permeability--permeability tests on 6 triaxial specimens vibrated to 60, 70 and 80% relative density gave permeability coefficients ranging from  $8.4\text{E-}4$  to  $1.0\text{E-}3$  cm/s (42.11:A3).

The vertical chimney drain is centered 35 ft downstream of the baseline throughout most of the section and reaches an elevation of

813.0 ft. The width of the drain varies, but is shown as 2 ft wide on Plate 1 (Detail C). At the base of the chimney drain is a 10 ft wide horizontal drain blanket (shown on Plate 1--Detail C). Drainage from the chimney drain and horizontal blanket drain was designed to exit through 29 sand drain outlets to a toe drain with outlet pipe at station 27+65.

## II.6 Instrumentation

The monitoring program for the main embankment consists of the measurement of foundation and embankment pore pressures and settlement surveys. The foundation porewater pressure measuring devices are the source of data for this research, and consist of both the pneumatic diaphragm-type and open standpipe type.

According to TVA engineers, the purpose of the main embankment piezometric instrumentation is to monitor the effectiveness of the cut-off trench and grout curtain and to monitor uplift pressures beneath the embankment (42.11:13).

The location and layout of the instrumentation was not finalized until later phases of construction, when more detailed information was available. TVA engineers designed the layout to provide information at locations where problems such as excessive uplift pressures, piping, and excessive water loss were potentially the most critical, based on geologic information, analysis, and experience with similar foundation conditions. As with other elements of the project, the layout and concept of the instrumentation program were reviewed and approved by the independent board of consultants.

### II.6.1 Location

The layout of the instrumentation is shown in Figures 4 through 6, and also on Plate 3. Figures 4 through 6 are simplified instrumentation plans and sections based on the detailed design blueprint (Plate 3). Figure 4 shows 5 ranges of pneumatic piezometers (ranges A through E) running transverse to the dam baseline. Also shown running roughly parallel to the toe of the dam (Figure 4) are 25 standpipe piezometers (range H).

The location of the pneumatic piezometers within the ranges (sections) are shown in Figures 5 and 6. Pneumatic piezometer designations consist of the range letter, followed by a letter designating the location with respect to the cutoff trench CL (upstream, downstream, or embankment), followed by a number designating the location with respect to the top of rock.

Figure 5, typical of ranges B through E, shows 4 lines of pneumatic piezometers. Three lines on the upstream side of the dam baseline are read from an upstream readout box on the crest of the dam. A fourth line, shown 93.5 ft downstream of the dam baseline is monitored from a readout box on the downstream berm. Also shown at the toe of the dam is the location of range H standpipe piezometers. Pneumatic piezometers U-1, D-1 and D-4 are located approximately 45 ft below the top of rock, while piezometers U-2, D-2 and D-5 are located approximately 15 ft below the top of rock. Piezometers U-3, D-3 and D-6 are located approximately 2 ft above the top of rock in the basal sand and gravel layer. One

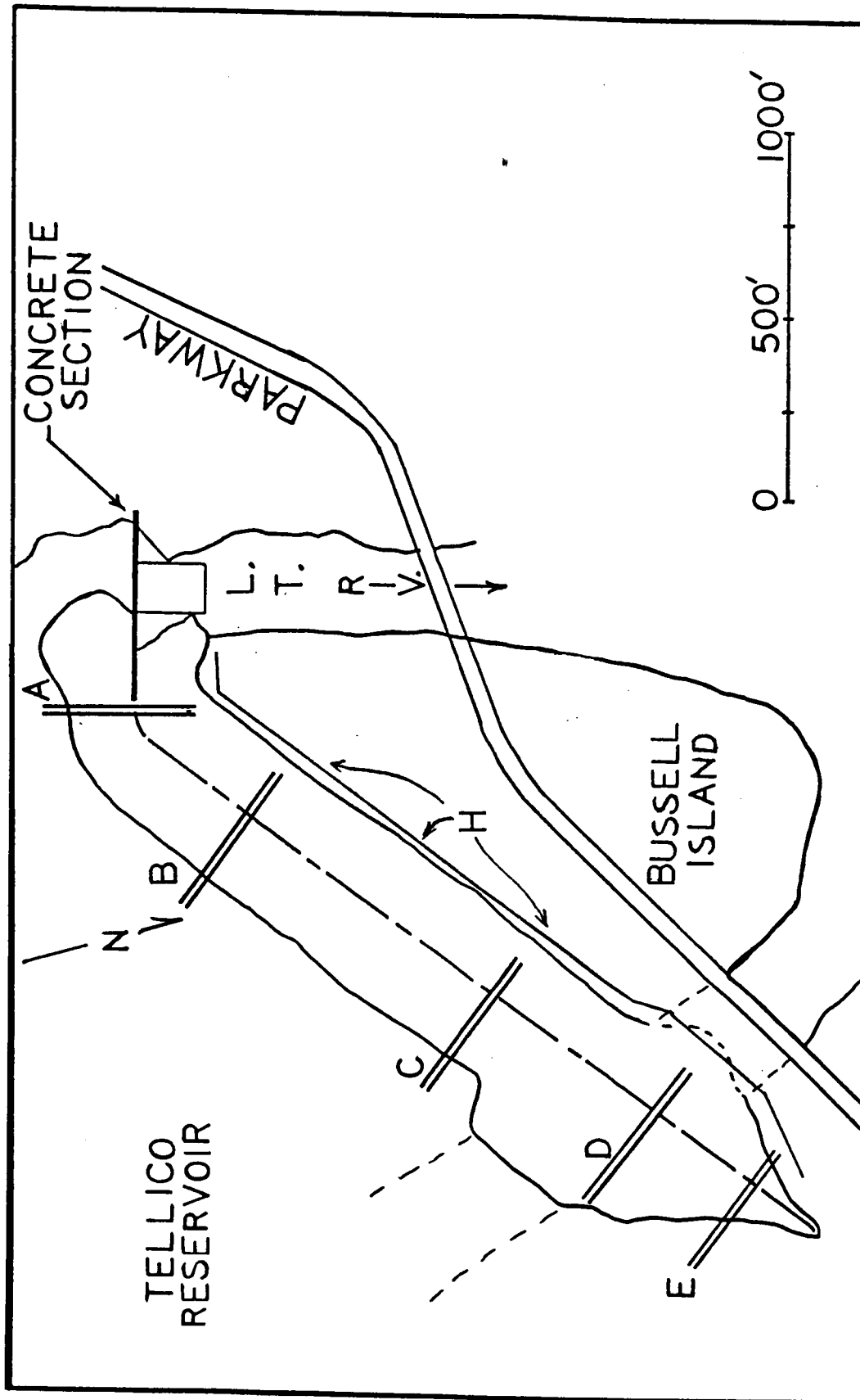


FIGURE 4. SIMPLIFIED PLAN VIEW OF INSTRUMENTED RANGES

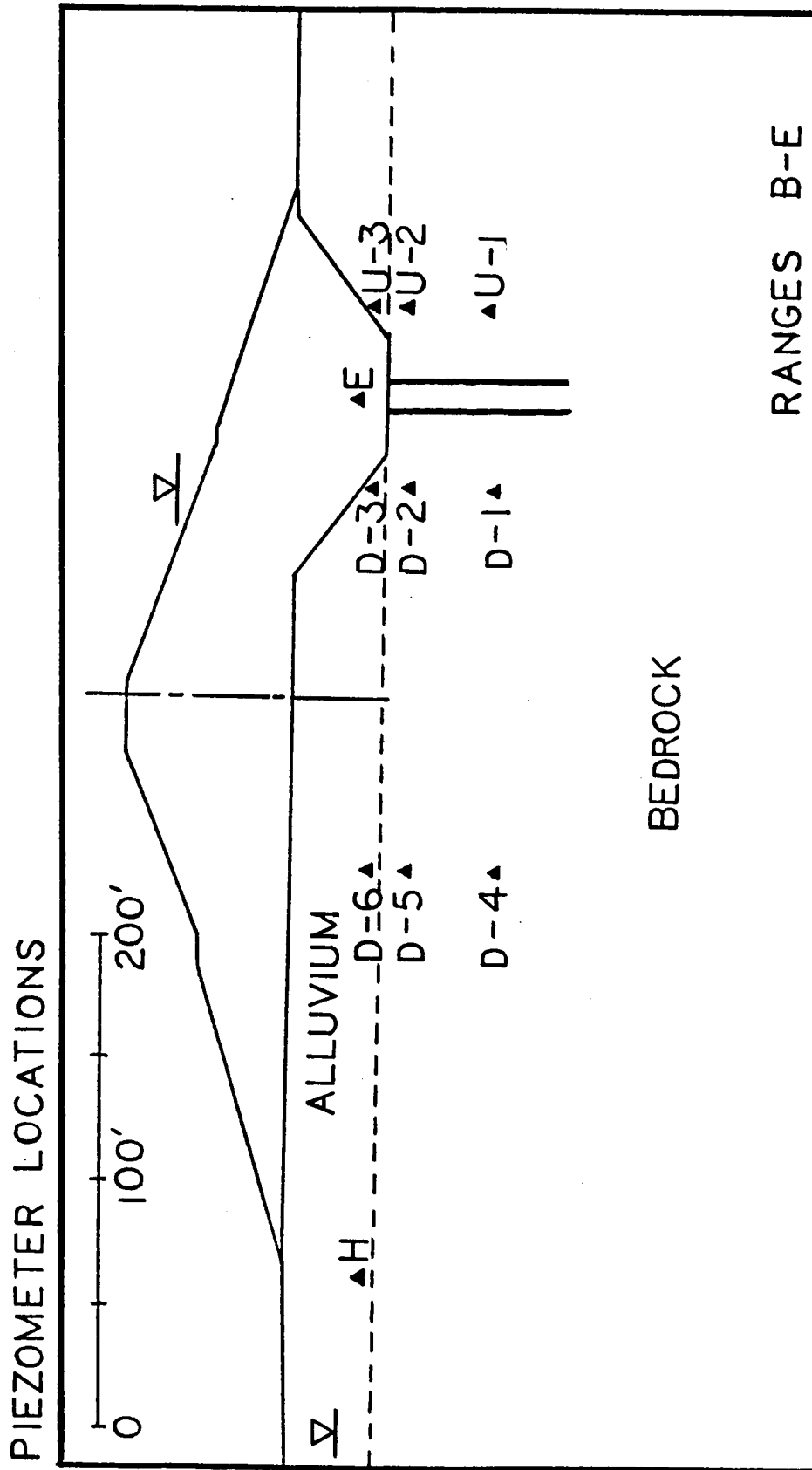


FIGURE 5. PIEZOMETER LOCATIONS FOR RANGES B THROUGH E

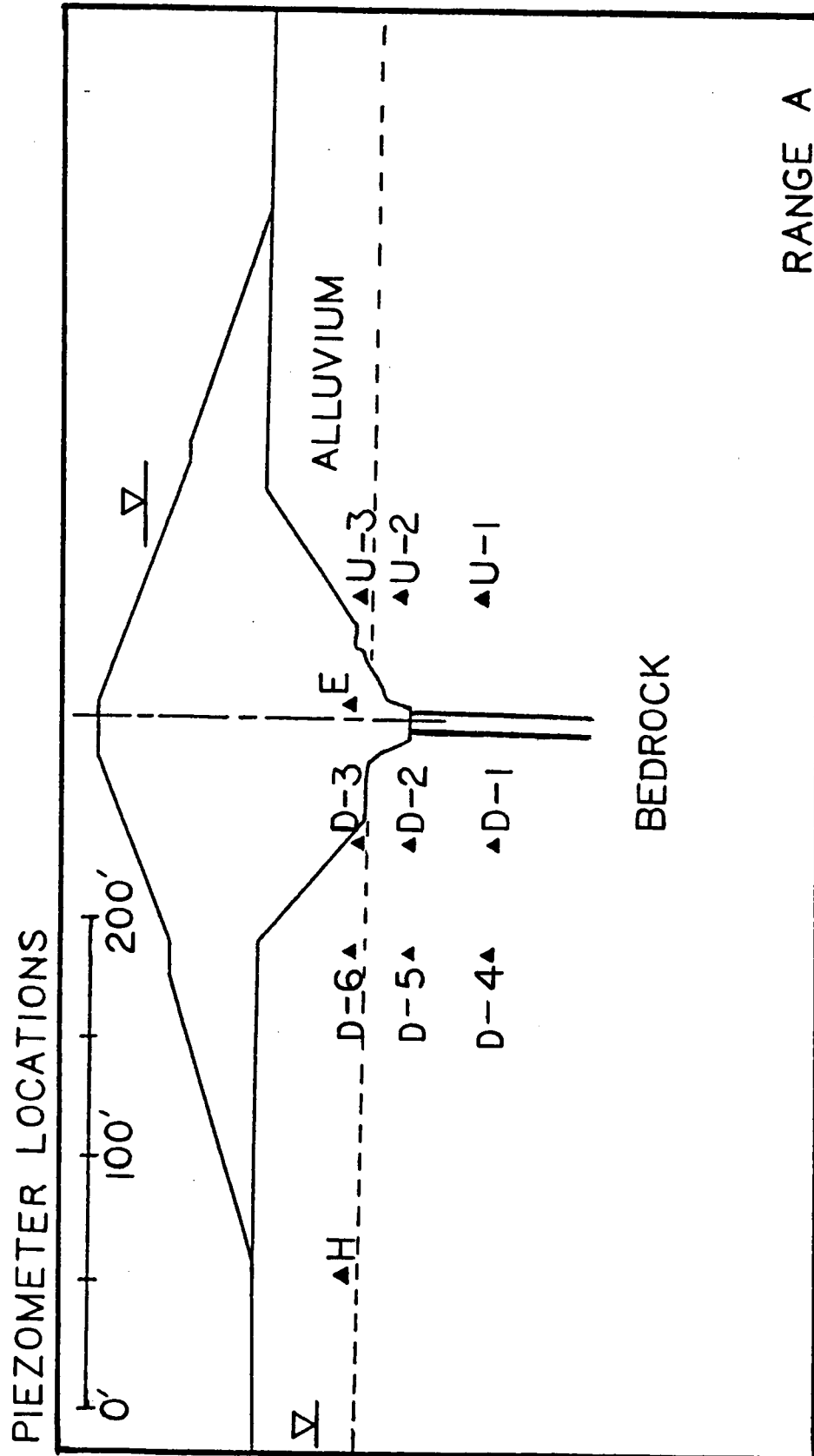


FIGURE 6. PIEZOMETER LOCATIONS FOR RANGE A

piezometer per range (designation E) is located in the cutoff trench. Because alluvium is absent in the original right channel of the river, only bedrock is monitored at range D. Figure 6 shows instrumentation for range A, which differs slightly from ranges B-E because of the location of the cutoff trench.

Within the general layout scheme shown, the pneumatic piezometers located in rock were specifically placed to monitor pressures in water-bearing seams. According to TVA engineers, each range of piezometers was to be aligned with a principal upstream-downstream joint set (with the exception of range A, which is oriented parallel to the end of the concrete nonoverflow dam) (42.5:5). As stated on Plate 3, note B, the piezometers in rock were to be located by borehole TV camera survey as well as by observation of core samples. Separate holes were drilled for each piezometer. Installation of the pneumatic piezometers began in late 1976, in the latter stages of embankment construction--according to TVA engineers, this was scheduled to help minimize construction delays and to protect the instrument tubes and components (42.5:6).

Range H (standpipe) piezometers were located near the toe of the dam, where TVA engineers anticipated that potential uplift pressures would be the most critical (42.11:4). Figure 4 shows the general location of this range. The piezometers are numbered from 1 to 26, starting at the downstream toe of the embankment near the concrete section and extending into the right abutment. Also shown on Plate 3 (plan) is one piezometer (H-8A) located farther upstream along an initially proposed alignment. Detail A1 (Plate 3, bottom) shows the location of the stand-

pipes with respect to the top of rock. Standpipes H-1 through H-15 monitor the sand and gravel layer approximately 1 ft above the top of rock, while the remaining range H piezometers extend 5 ft into bedrock.

One additional piezometer (not subsequently analyzed) deserves mention because it was installed after discovery of a sinkhole in January of 1984. Piezometer F-1s monitors a sinkhole on the right abutment adjacent to the Tellico parkway, approximately 365 ft downstream of the baseline at station 32+39.08. According to TVA design blueprints, a 7 ft diameter, 8 ft deep sinkhole discovered by maintenance personnel apparently developed rapidly during the period January 9-13, 1984 (43:22W800). According to design notes, this piezometer was installed in February 1984 to monitor pore pressures near the sinkhole and supplement existing instrumentation.

#### II.6.2 Details of Instrumentation

The pneumatic piezometers selected for monitoring ranges A through E operate by the process of pressure equalization between in-situ fluid pressures and a measurement fluid. These piezometers are Gloetzl brand pneumatic piezometers, marketed and supported in the U.S. by Terra-metrics, a Division of Slope Indicator Company, Seattle, Washington. The piezometers were originally developed by Franz Gloetzl in the 1950s while serving on the faculty of the University of Karlsruhe, West Germany (51:2).

Figure 7 shows a schematic diagram of a Gloetzl piezometer. Principal features of the device are a diaphragm, bypass valve, filter,

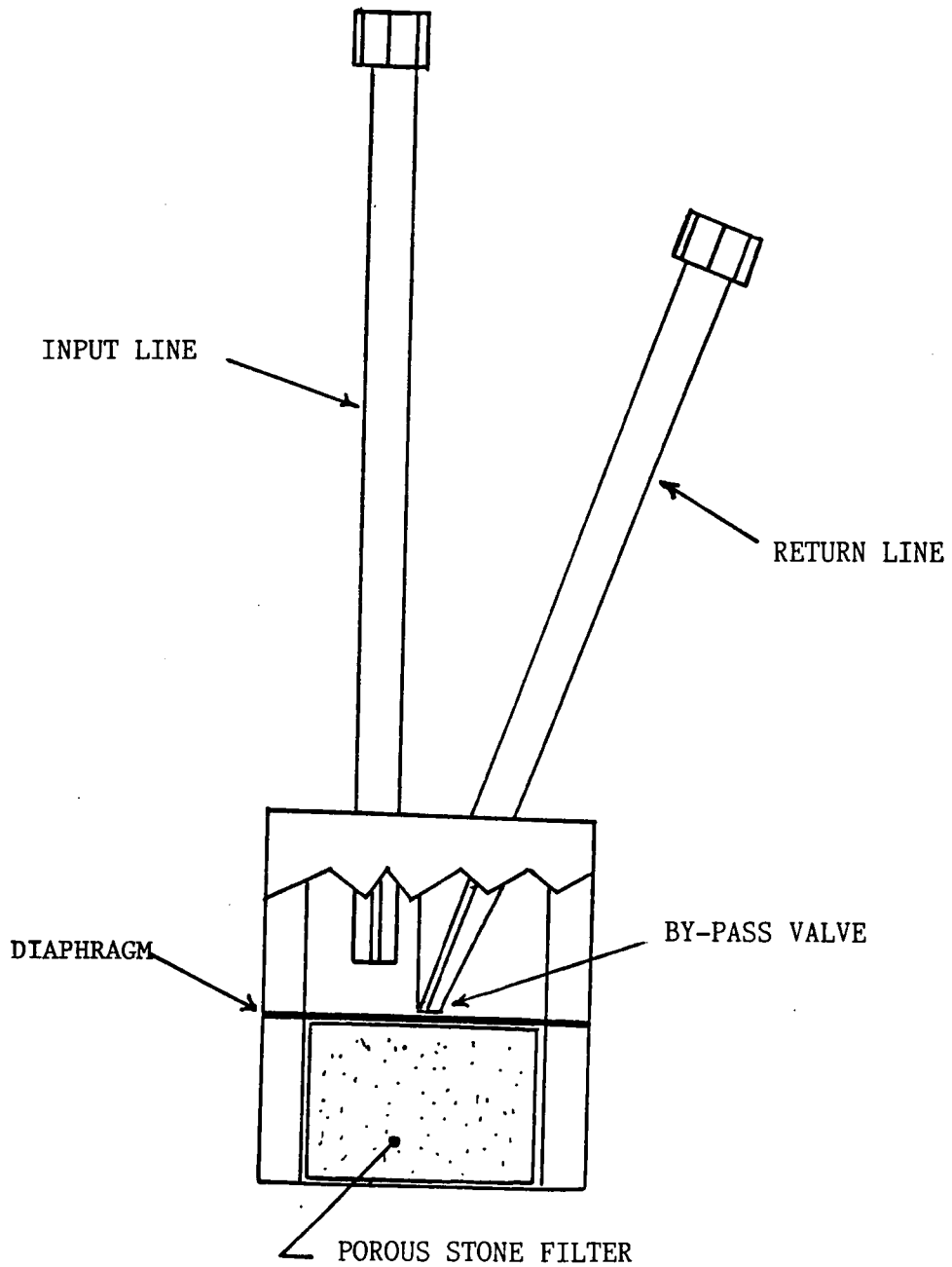


FIGURE 7. SCHEMATIC DIAGRAM OF A GLOETZL PNEUMATIC PIEZOMETER

input line, and return line. Pressure from the fluid system being measured acts on the diaphragm, preventing circulation between the input and return lines until pressure introduced into the input line slightly exceeds the external loading pressure (51:2). Pressure is applied to the input line with a pressurized nitrogen tank in order to read the instrument. A slight movement of the diaphragm occurs when a pressure excess in the input line is reached, allowing the gas to circulate to the return line. At this point, the inflow of gas to the input line is cut off. As the gas continues to circulate through the bypass, the measurement fluid (gas) pressure and in-situ pore pressures start to equalize, causing the diaphragm to shut off the bypass. When the valve closes, the pressure in the input line is read from a gage and taken as a measure of pore pressure. Design of the instrument does not permit the recording of negative gage pressures.

Preconditioning of the Gloetzl piezometers prior to installation consisted of filling the passages in the cell body with a kerosene-oil mixture and purging air from the cell body. Entrained air from the filter stone was removed by partially immersing the stone in a kerosene-oil mixture and allowing capillary action to displace the air.

As previously stated, the Gloetzl piezometers in rock were installed by locating a water-bearing seam using core observation and borehole TV camera survey. The installation procedures described here are summarized from design notes on the blueprint "Main Embankment-Plans Sections and Details-Sheet 3" (43:22N205). After completion of the borehole, the piezometers were wrapped in filter sand, securely tied

with a cotton sock, and placed in the hole with backfilled filter sand. After backfilling a minimum of 18 in of filter sand above the piezometer, the hole was sealed using bentonite pellets, followed by grout. For piezometers installed in the sand and gravel, holes were drilled to rock, backfilled with approximately 2 ft of filter sand, and the piezometers were placed similarly, wrapped in a cotton sock with filter sand. The holes were further backfilled with sand and sealed with bentonite pellets at the alluvium-embankment contact or the contact between the fine sand and alluvial silts, depending on location. Piezometers installed in the embankment cutoff trench were located at the approximate precutoff trench elevation of bedrock. The piezometers were wrapped with the cotton sock full of filter sand, but the backfill material in the bottom of the hole was, in this case, embankment material passing the No. 4 sieve. Above this, a mixture of embankment material, filter sand, and bentonite powder was used to complete backfilling.

As shown on Plate 3 (sections A1-A1 and E1-E1), PVC tube races were used to house piezometer intake and return lines. The lines are 2 1/4 in nylon tubes. General procedures for installation are noted on Plate 3. It was specified that extreme care be taken during installation not to damage the piezometers and that connections be made in a "scrupulously clean environment" (Plate 3). The remote readout of the Gloetzl piezometers is performed at a series of manholes, which house input and return line terminals for the respective piezometers.

The standpipe piezometers (range H) consist of stainless steel wellpoints with a 1 3/4 in outer diameter. Details of the standpipe

piezometers are shown on Plate 3 (Detail A1). The chimney drain filter sand was used to backfill the wells in the vicinity of the wellpoint. As with the pneumatic piezometers, bentonite pellets were used to seal off the holes at the upper contact of the strata for which measurements were to be made. For piezometers H-1 through H-15, wellpoints were installed in the basal sand and gravel layer, and the bentonite seal was made at the bottom of the alluvial clays and silts, while for H-16 through H-26, where bedrock is monitored, the seal was made at the top of rock.

#### II.6.3 Headwater and Tailwater Gages

The Tellico headwater gage is located in a concrete housing on the upstream face of the dam at station 30+50 (Plan View, Plate 3). The closest tailwater gage to Tellico Dam is the Fort Loudon Dam tailwater gage, located nine feet downstream from the face of Fort Loudon Dam (41:1). This gage is approximately one river mile upstream from the confluence of the Tennessee and Little Tennessee Rivers on Watts Bar Reservoir. Both gages are Stevens long distance selsyn transmitters with graduated float, transmitting to a receiving indicator in the Fort Loudon Dam control room.

#### II.6.4 Instrumentation Observation Procedures

After closure of the dam on November 29, 1979, the Gloetzl and standpipe piezometers were first monitored weekly during reservoir filling (42.11:6). After this period, the observation frequency was made monthly.

TVA Field Operations East personnel presently observe the piezometers monthly and also make other routine dam-safety-related inspections. The Gloetzl piezometer readout terminals are readily accessible by automobile from service roads on the dam crest and downstream berm. Routine procedures for reading the Gloetzl piezometers consist of the following:

1. The piezometer input line terminal is connected to a tank of pressurized nitrogen gas with nylon tubing. A gage mounted to the tank and graduated to the nearest 0.5 psi monitors input line pressure.

2. The piezometer outlet line terminal is connected to nylon tubing, the end of which is inserted in a container of water.

3. Gas is introduced to the inlet line at a pressure slightly exceeding the expected value for a given piezometer until bubbles from the outlet line (immersed in water) signal that bypass has occurred.

4. The valve on the nitrogen tank is shut off, and when bubbling of the outlet line ceases, the gage on the input line is read and interpolated to the nearest 0.1 psi.

5. If the observed pressure is deemed unusual, the procedure is repeated. Pressure values are recorded on field notes and converted to pressure head (ft).

Standpipe piezometers are read by measuring the distance from the top of a 3/4 in riser pipe to the water surface. This is accomplished with a Soiltest Model DR760 sounding tape, which consists of a conductivity sensor and metal measuring tape attached to a spool. The spool houses a conductivity meter that registers when the conductivity sensor

comes into contact with water. The sensor and tape are lowered into the well until contact of the sensor with the water surface registers on the conductivity meter. The sensor is then lifted up and down several times to verify contact with the water surface--then, the length of tape in the pipe is noted. This quantity is subtracted from the surveyed pipe elevation to yield a piezometric elevation.

### III. PIEZOMETRIC MONITORING--THEORY AND APPLICATION

Piezometric monitoring of earth dam projects can be an important indicator of embankment and foundation performance. Various analytic tools exist for predicting the water pressure distribution in a flow system, but assumptions must invariably be made regarding material properties and boundary conditions. As with other types of monitoring, piezometric monitoring is used to verify the accuracy of design assumptions and provide data on changing conditions throughout the life of the structure.

The purpose of this chapter is to present some physical laws governing groundwater flow, summarize existing techniques for processing and analyzing piezometric data, and present some case examples of piezometric monitoring for dam safety.

#### III.1 Equations of Groundwater Flow

##### III.1.1 Darcy's Law

Darcy's law is a fundamental empirical relationship with wide application in science and engineering. Figure 8 is a schematic diagram of the experimental condition for proving Darcy's law. The device consists of a cylindrical tube full of porous media with two inserted standpipes. For steady ( $Q = \text{const.}$ ) flow of a fluid through the soil in the tube, Darcy's law states that the discharge velocity through the porous media is equal to the product of the hydraulic conductivity and the hydraulic gradient:

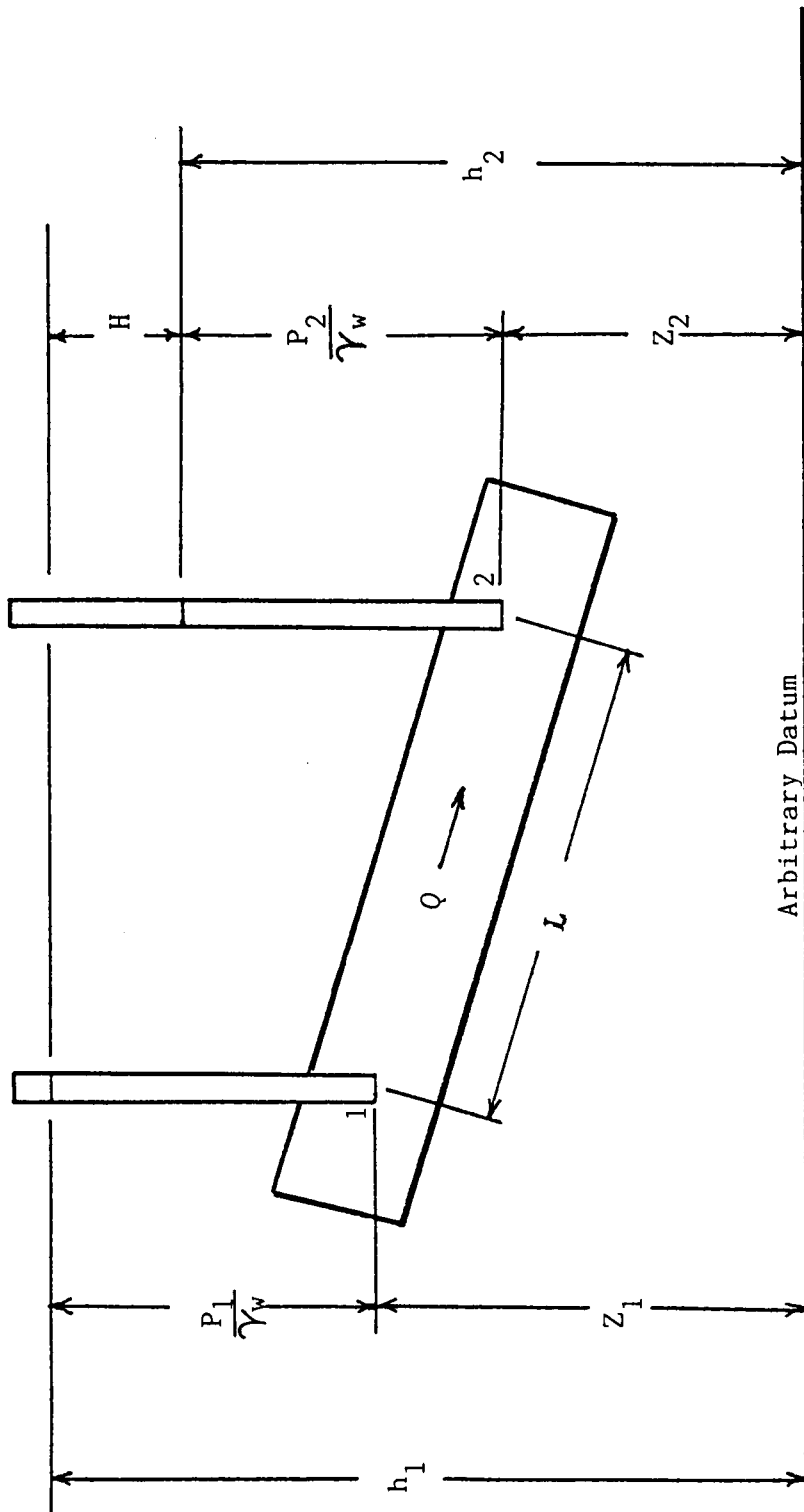


FIGURE 8. EXPERIMENTAL CONDITION FOR PROVING DARCY'S LAW

$$v = Ki , \quad (1)$$

where

$v$  = discharge velocity,

$K$  = hydraulic conductivity, and

$i$  = hydraulic gradient.

The discharge velocity ( $v$ ) is a macroscopic velocity defined as the quotient of total flow through a cross-section and the area of the section.

The hydraulic conductivity ( $K$ ), also referred to as the coefficient of permeability, is a constant of proportionality dependent on both the porous media and the fluid flowing through it. Harr (18:8) discusses a physical permeability ( $k$ ) which is independent of fluid properties and gives the following relationship between physical permeability and hydraulic conductivity:

$$K = \frac{k\gamma}{u} , \quad (2)$$

where

$\gamma$  = unit weight of fluid, and

$u$  = absolute (dynamic) viscosity.

Substitution of Equ. 2 into Equ. 1 shows that the discharge velocity is proportional to fluid unit weight and inversely proportional to fluid viscosity. Unit weight is the product of fluid density ( $\rho$ ) and a

gravitational constant ( $g$ ), while the coefficient of viscosity is a proportionality constant relating local shear stresses in a moving fluid to the strain rate of the fluid. In order to investigate the effects of temperature on hydraulic conductivity, the combined effects of fluid density and viscosity may be represented by the kinematic viscosity ( $\nu$ ). Since  $\nu = u/\rho$ , Equ. 2 may be written as:

$$K = \frac{k}{\nu} g . \quad (3)$$

Between the temperatures of 50°F and 68°F the kinematic viscosity of water decreases approximately 23%. However, because of relatively low temperature fluctuations in most civil engineering problems (as is the case for seepage through dams) and also because water is relatively incompressible, the hydraulic conductivity expressed by Darcy's law is usually assumed to be a constant.

The hydraulic gradient ( $i$ ) is a potential gradient, defined by Harr as the space rate of energy dissipation per unit weight (18:5). The hydraulic gradient may be defined from the quantities in Figure 5 as:

$$i = -\lim_{L \rightarrow 0} \frac{\Delta H}{\Delta L} = -\frac{dH}{dL} . \quad (4)$$

### III.1.2 Bernoulli's Equation

From Figure 8, an equivalence between the vertical distances associated with points 1 and 2 can be stated as:

$$\frac{P_1}{\gamma} + Z_1 = \frac{P_2}{\gamma} + Z_2 + H . \quad (5)$$

Equ. 5 is a version of Bernoulli's equation for steady flow, modified for negligible velocity head differential between points 1 and 2 and for energy loss due to viscous resistance within the porous media. The original Bernoulli equation for frictionless, unsteady flow through an infinitesimal streamtube was originated in the eighteenth century by Daniel Bernoulli and Leonhard Euhler (59:159). The equation, as derived by White (59:161) using conservation of mass and momentum requirements for an elemental control volume, is as follows:

$$\int_1^2 \frac{\partial V}{\partial t} ds + \int_1^2 \frac{dP}{\rho} + \left[ \frac{(V_2^2 - V_1^2)}{2} \right] + g(Z_2 - Z_1) = 0 , \quad (6)$$

where

$t$  = time,

$V$  = fluid velocity,

$s$  = streamline direction, and

$P$  = pressure.

The units for Equ. 6 are in terms of mechanical energy per unit mass of fluid. The assumptions of steady incompressible flow, negligible velocity differential between points 1 and 2, and viscous energy loss through a porous media results in the simplification of Equ. 6 to Equ. 5. Equ. 5, which has been divided through by  $g$ , has units of length representing mechanical energy per unit weight of fluid (head).

In terms of energy, the terms in Equ. 6 act on a unit mass of fluid and (from left to right), represent work done on the fluid raising the linear momentum between points 1 and 2 along a path S, work done on the fluid raising it from P1 to P2, work done on the fluid raising it from V1 to V2, and the work required to lift the fluid from Z1 to Z2.

The hydraulic head ( $h$ ), also known as the total head, is a measure of fluid potential for flow. Hydraulic head is defined as the sum of the elevation head ( $z$ ), the pressure head ( $P/\gamma_w$ ), and the velocity head ( $v^2/2g$ ). Velocity heads (not shown on Figure 8) are usually taken to be negligible in porous media flow applications, resulting in the following definition for hydraulic head at any point:

$$h = h_p + z , \quad (7)$$

where

$h_p$  = pressure head.

### III.1.3 The Diffusion Equation

The diffusion equation, given by Freeze and Cherry (1965), is a partial differential equation of transient flow through a saturated isotropic porous media. The equation can be derived by substituting Darcy's law into the equations of continuity for transient flow. For an elemental control volume, the net mass flow rate through the boundaries is equal to the mass rate of water produced by compaction due to a change in porosity plus the mass rate of water produced by expansion

due to changes in density (13:65). The equation for this condition, as given by Freeze and Cherry (13:65), is:

$$\frac{\partial}{\partial x} (K_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (K_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z} (K_z \frac{\partial h}{\partial z}) = S_s \frac{\partial h}{\partial t} , \quad (8)$$

where

$S_s$  = specific storage.

The specific storage ( $S_s$ ) is defined as the volume of water released by a unit volume of saturated porous media under unit decline in hydraulic head. Substitution of Darcy's law in the x, y, and z directions and assumption of a homogeneous, isotropic, porous media leads to the diffusion equation, as given by Freeze and Cherry (13:65):

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = \frac{S_s}{K} \frac{\partial h}{\partial t} , \quad (9)$$

#### III.1.4 LaPlace's Equation

LaPlace's equation is a special case of the diffusion equation where flow is steady ( $\partial h / \partial t = 0$ ). The most common derivation of the equation is for two-dimensional flow. For steady flow through a saturated, homogeneous, isotropic media in the x-y plane, LaPlace's equation reduces to the following:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = 0 . \quad (10)$$

The solution to LaPlace's equation as stated in Equ. 10 is a function  $h(x,y)$  describing magnitude of the hydraulic head. LaPlace's equation is also satisfied by two conjugate harmonic functions, the velocity potential and stream functions. The velocity potential function ( $\phi$ ) is defined as:

$$\phi = -K(h_p + z) + C = -Kh + C , \quad (11)$$

where

$C$  = arbitrary constant.

The stream function ( $\psi$ ) is defined as:

$$v_x = \frac{\partial \psi}{\partial y} \quad ; \quad v_y = - \frac{\partial \psi}{\partial x} . \quad (12)$$

In a system described by Equ. 10, the loci of the path of flow of individual particles (streamlines) satisfy the relationship:

$$\psi = \text{const.}$$

Since the velocity potential is directly proportional to hydraulic head, it follows that lines of equal hydraulic head (equipotential lines), are the loci of points for which:

$$\phi = \text{const.}$$

The properties of the stream and velocity potential functions form the basis for flow net construction, the widely used graphical solution to the 2-dimensional version of LaPlace's equation (Equ. 10).

Properties of the flow net are discussed with the use of Figure 9. This figure shows a portion of a flow net, consisting of streamlines and equipotential lines. For the square of dimensions  $c$ , the hydraulic gradient can be approximated as:

$$i = \frac{\Delta H}{c} = \frac{H}{(N_t)(c)}, \quad (13)$$

where

$N_t$  = total number of equipotential drops, and

$H$  = total head lost in the system.

The total discharge per unit width ( $q$ ) is:

$$q = KH \frac{(N_f)}{(N_t)}, \quad (14)$$

where

$N_f$  = total number of flow channels.

### III.1.5 Applicability of Darcy's Law

According to Harr, the validity of Darcy's Law was investigated by Reynolds in the late 1800s, who found that Darcy's Law applied only within the range of laminar flow (18:6). For flow through soils the Reynolds number is:

$$Re = \frac{vD}{\nu} \quad (15)$$

where

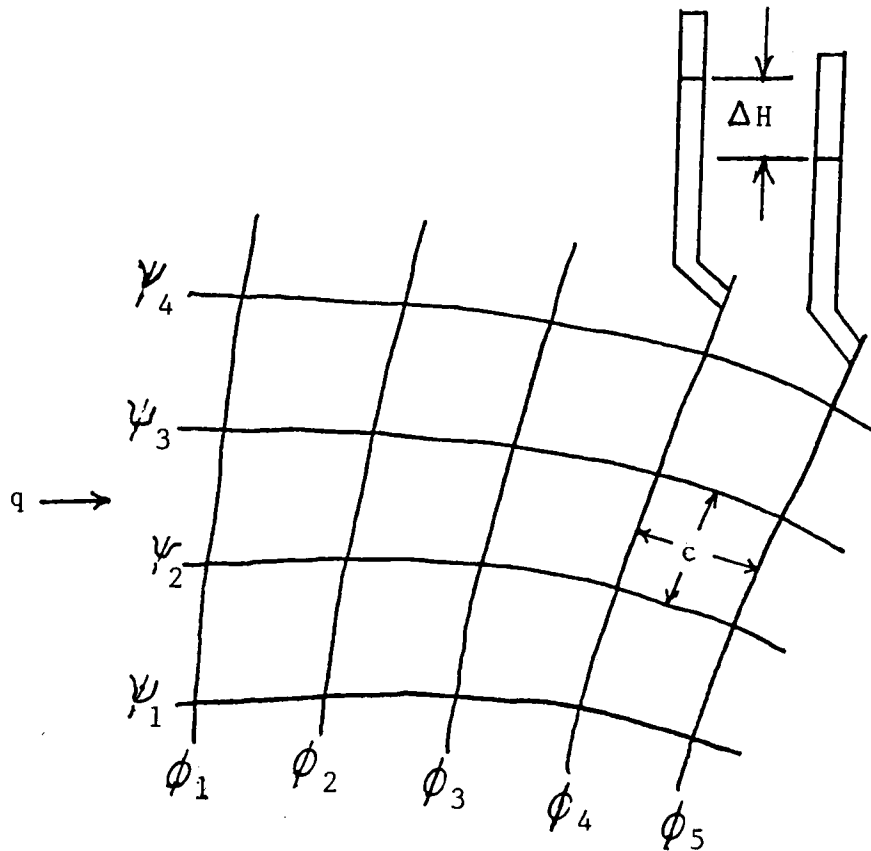


FIGURE 9. SCHEMATIC DIAGRAM OF A PORTION OF A FLOW NET

$D$  = mean soil particle diameter.

The critical value of the Reynolds number above which turbulent flow occurs is approximately 1. In the case of turbulent flow, Reynolds found that the hydraulic gradient approached the square of the velocity (18:6). According to Freeze and Cherry, flow rates often exceed the upper limit of Darcy's law in karstic limestones but rarely exceed this limit in "nonindurated" (not hardened) rocks and granular materials (13:73).

In spite of the fact that flow velocities in individual fractures might exceed assumptions for Darcy's law, seepage problems involving jointed rock have been attempted by assuming that the strata is an equivalent continuum in which Darcy's Law applies. According to Freeze and Cherry, other solutions can be classified as involving a noncontinuum approach, for which flow through individual fractures is modeled (13:73).

### III.1.6 Flow in Fractured Rock

#### III.1.6.1 The Noncontinuum Approach

The noncontinuum approach for flow through fractured rock is based on the Navier-Stokes equations for conduits. According to White, these equations were derived by C. L. M. H. Navier and Sir George G. Stokes, and are second-order nonlinear partial differential equations based on the differential equation of momentum for a newtonian fluid (59:224). Snow (39:1274) presents a form of these equations for the average

velocity ( $v'$ ) per unit width of a parallel plate conduit, derived for the condition of slow nonturbulent single phase flow of an incompressible fluid:

$$v' = - \frac{B^2 I g}{12 \nu}, \quad (16)$$

where

$B$  = aperture width,

$I$  = projection of hydraulic gradient onto the conduit plane, and

$\nu$  = kinematic viscosity.

An equation for flow through a series of parallel plates is obtained by multiplying Equ. 16 by the area through which flow occurs. Snow (39:1275) presents an equation of flow through a unit cube for the general case of differing plate apertures and conduit spacing:

$$q = - \frac{g I}{12 \nu} \left( \sum_{i=1}^N B_i^3 \right), \quad (17)$$

where

$N$  = number of apertures per unit width of material (aperture spacing), and

$B_i$  = width of  $i$ th aperture.

Numerous recent research has been directed toward the refinement of Equ. 16 and Equ. 17, but according to Tsang (53:1209) most models for flow through fractured rock are based on these equations. Observation

and experiment has shown that flow is also a function of effective stress. According to Freeze and Cherry, expansions and contractions of fracture apertures which occur as a result of applied stress can effect the value of the hydraulic conductivity  $K$  (13:74). As discussed by Tsang, increases in effective stress cause increased tortuosity and decreased connectivity in fractured rock (53:1209).

#### III.1.6.2 The Continuum Approach

With the continuum approach, the fractured media is represented as a Darcian continuum. Snow (39) equates Darcy's law with Equ. 17 to solve for an equivalent physical permeability ( $k$ ):

$$k = \frac{N b^3}{12}, \quad (18)$$

where

$b$  = average aperture diameter.

For the more general case of dispersed fractures, Snow replaced the aperture spacing  $N$  with a frequency distribution representing the specific surface of flow and derived a tensor representation of permeability (39:1288). In conclusion, Snow states that the tensor permeability of jointed granular porous media is obtained by superposing the separate contributions of the porous media and the fractures (39:1288). In addition, he also found (13:75) that a Darcian continuum representing three

equal, orthogonal joint sets is statistically isotropic, with permeability:

$$k = \frac{N b^3}{6}, \quad (19)$$

### III.2 Applied Monitoring

Piezometric monitoring of embankment dams and foundations for dam safety is undertaken throughout the world by a number of different organizations, including private consultants, owners, and government agencies. Information exchange on the state of the art in monitoring occurs via formal publication of papers, informal communications, and meetings of technical societies and committees. This section presents some considerations concerning instrumentation performance, followed by a discussion of case examples of piezometric monitoring and analysis.

#### III.2.1 Instrument Performance

Instrument performance is a critical aspect of the monitoring program. Malfunctioning piezometers in embankments and foundation materials are generally difficult and costly to replace. A major problem confronting the engineer responsible for analysis and interpretation is differentiating valid data from erroneous data caused by instrument malfunctions or from reading errors. In recognition of this problem, a need was identified for research on the reliability, durability and general performance of new instrumentation at the ICODS Dam Safety

Research Coordination Conference of 1982 (57:III-23). This aspect of monitoring is obviously important, since improper conclusions regarding structure performance and safety could be drawn from erroneous data.

#### III.2.1.1 Pneumatic Piezometers

According to Dunnicliff, pneumatic piezometers have been used in the USA for over 20 years, and have been used extensively and successfully for the last decade (8:8). Since many of the instruments installed during this period are still operating properly, the long-term reliability of these instruments still remains to be seen. According to Penman, leakage of the bypass valve due to dirt and wear is a problem that affects the reproducibility of results (30:17). Blockage of the lines with debris and leakage of the measurement fluid through connections also causes problems.

In a summary of Canadian dams constructed by the Prairie Farm Rehabilitation Administration (PFRA), Peters and Long report that of 140 pneumatic piezometers installed, 15% failed and 7% were either "lost or destroyed" (32:28). Here, loss of several instruments after installation due to subsequent construction activities seems likely. Faulty installation procedures and failures of the diaphragm and tubing were cited as causes for failure (32:35). The maximum in-place age of the piezometers studied by Peters and Long was 15 years (32:28).

In a 1982 summary on the use of piezometers in earth dam impervious sections, Sherard notes that pneumatic piezometers were in wide use by the mid-1960s in many large projects, with generally satisfactory

results (35:129). According to Sherard, as of 1980, all pneumatic piezometers installed in the Briones Dam in California (constructed 1961-1964) were functioning properly, while all the USBR twin tube piezometers installed had ceased to function (35:129). Sherard contrasts the record of pneumatic piezometers at Briones with the installation of 140 piezometers at the Puchina Dam in Columbia (under construction in 1980), where difficulties were encountered in producing reproducible results with 50 piezometers of a certain brand (35:130).

#### III.2.1.2 Standpipe Piezometers

According to Penman, the standard standpipe or well point piezometer is the oldest, most widely used pore water pressure measuring device (30:16). In recommending long-term performance instrumentation for embankment dams, Dunnicliff emphasizes that the standpipe piezometer should be the first choice (8:7). Commonly encountered problems with standpipe piezometers are loss or destruction and clogging of the wellpoint and/or surrounding filter material. Backflushing is commonly employed to treat the latter problem. According to Peters and Long, in a 40 year period approximately 1200 standpipe piezometers were installed in Canadian PFRA dams, and of these, 10% were destroyed or lost and 5% failed (32:28). Here again, as for pneumatic piezometers, loss was probably caused by subsequent construction activities. According to Dunnicliff, a falling or constant head test can be used to verify that the instrument is functioning if a base test was initially made for comparison (8:8).

### III.2.2 Case Examples

While case examples in the analysis of piezometric monitoring data are found in the literature, the results of many monitoring efforts have yet to be published. In most published examples, piezometric data is generally presented as one aspect of a detailed evaluation of project data, which might also include embankment settlement, movement, and seepage data. Many of the published examples encountered involved a comparison of data with theoretically determined design values. Several examples describe the use of computers in processing and analyzing the data. The use of statistics as an aid to evaluation of data is also found in the literature but is not well-established in practice.

#### III.2.2.1 Use of Computers for Monitoring

The use of computers in the processing of data from Guri Dam (Venezuela) is described by De Fries (7). In discussing the advantages associated with the computer processing of instrumentation data, De Fries notes that such systems, if properly planned, can relieve the instrumentation staff of a large fraction of routine work such as processing, filing, plotting, and reporting of data (7:144). This has the potential for reduction of human error. According to De Fries, a properly designed system should limit the time necessary for processing, so that the data can be reviewed in time to detect important trends, and also provide field personnel with the capacity to detect invalid or abnormal readings (7:144). De Fries further describes the use of computer flags

based on "normal ranges" and "acceptable rates of variation" for inclusion in routine reports (7:149). Computer plots of reservoir and piezometric elevations and correlative plots of related variables are also presented in this work. According to De Fries, only those computer systems that rely heavily on the use of graphical display can be successful in monitoring for dam safety (7:145).

The Army Corps of Engineers (COE) St. Louis District Office utilizes an automated data processing system for their hydroproject structural integrity data. According to J. D. Lytle (oral communication, April 1984), graphical display plays an important part in detecting unusual observations and possible problems. The COE, St. Louis District, first used computers to receive field data via teletype and produce tabular output and line-printer plots. After gaining experience and knowledge in the field of automated data processing, they expanded into the generation of more sophisticated plots and charts (26:510).

The Bureau of Reclamation (Bu Rec), Structural Behavior Branch, has been utilizing an automated system for their structural integrity data since 1981. The following observations are based on a visit to the Bu Rec office at the Federal Research Center in Denver, Colorado in June of 1984. Instrumentation data from approximately 100 earth dams and 60 concrete dams is received and processed. Hand-held data entry devices are used to record field data. Upon arrival to the field office, field personnel then transmit the readings to the mainframe computer. Bu Rec personnel review a variety of graphical products in the process of routine validation and assessment of the data.

### III.2.2.2 Short-term Piezometric Monitoring Examples

Several examples on monitoring during construction phases show the different analytical techniques applied for this phase in comparison with many postconstruction phase analyses. As will be further discussed, many analyses of long-term piezometric data assume steady flow. In contrast, analysis of data during construction usually necessitates the use of transient flow equations. A review of several cases of construction and first-filling phase monitoring is therefore discussed.

In an analysis of India's 128 m high Ramanga Dam, Goel and Das used a partial differential equation based on assumptions from Terzaghi's one-dimensional consolidation theory to analyze consolidation of a clay layer increasing in thickness with time (15:417). This equation, originally presented by R. E. Gibson in 1958, was solved for Ramanga Dam using the finite difference method (15:417). As applied, the method enables the prediction of pore water pressures during construction. A comparison of theoretical data and observed values showed that at higher total pressures, observed values exceeded those predicted by Gibson's equation in several cases (15:420). According to Goel and Das, selection of values for the coefficient of consolidation and Skempton pore pressure coefficient affects the accuracy of this method (15:420).

The monitoring of the Gardiner Dam in southern Saskatchewan, as reported by Peters and Long (32), provides a perspective on the use of monitoring data in design and operation of a structure. Instrumentation was first used to monitor stage construction of a 65 m high embankment

founded on layered sandstones and shale. According to this report, high movements recorded by slope indicator gages detected a shear zone developed in shale immediately overlying a pervious sandstone--this necessitated design changes involving a flattening of the downstream slope (32:41). According to Peters and Long, piezometers subsequently installed in the vicinity of the shear zone have detected pressures consistently higher than hydrostatic, causing computed stability safety factors to approach unity (32:41). In this case, a comprehensive long-term monitoring program was considered essential to the continued safety of the project.

#### III.2.2.3 Long-Term Piezometric Monitoring Examples

Szalay and Marino (38) discuss the use of piezometers in the long-term monitoring of Tarbela Dam, a 460 ft high embankment dam in Pakistan. According to Szalay and Marino, the dam, which is founded on deep pervious alluvium, developed over 300 sinkholes in an upstream drainage blanket during first filling (38:75). Examples of the computer processing of the piezometric data are limited to a tabular display of heads and potentials, changes in potentials since the last observation, and computer plots of piezometric elevations vs time. Contour plots of piezometric potential were periodically prepared for a plan view of the dam and compared with previous plots (38:92). According to Szalay and Marino, piezometric instrumentation helped detect early damage to an intake tunnel and also recorded declines in potential in response to repair of the upstream drainage blanket (38:92-100).

An analysis of piezometric monitoring in jointed, karstic rock on the left bank of Jordan's 100 m high King Talal Dam is presented by Guzina and Nikolovski (17). During the design process, a complex series of faulted sandstone, limestone, and dolomites were grouped into 6 seepage zones (17:972). According to Guzina and Nikolovski, monitoring showed that significant local changes in the piezometric field occurred through time--this was attributed to changes in the geometry of seepage paths (17:980). The dissolution of joint filling material was given as the primary cause of these changes (17:982).

Amaya, Cubillos and Sierra performed an analysis on short- and long-term piezometric data from Chivor Dam, a 237 m high rockfill earth core structure located in Columbia (1). Data from 38 pneumatic piezometers in the clay core were evaluated, and a comparison between measured pore pressures and pressures determined from a theoretical flow net was made (1:19). While the authors acknowledged that LaPlace equations were not fully applicable due to incomplete saturation of core material, anisotropy, and continuing consolidation, flow nets were nevertheless used. Noting that pore pressures had not fully dissipated since construction and that the reservoir level fluctuates 80 m during 8 months of operation, the authors chose to analyze flow for the full condition prevailing 4 months a year (1:23). The authors defined excess pore pressure as the percent difference between actual and theoretical values and presented a table of results (1:25). Computations for data observed approximately 2 years after first filling showed observed excess pore pressures in the core to be less than 25% of the theoretical

pore pressures (1:25). The authors attributed this difference to pore pressures built up during construction (1:29).

Loukola and Slunga present an analysis of piezometric monitoring data for Hautapera Dam, a 22 m high Finnish earthdam (25). According to the authors, seepage spots and a minor slip on the downstream face of the dam developed after first filling of the reservoir in late 1975, necessitating repair work (25:294). At this time, 51 standpipe piezometers were installed in the dam to monitor flow conditions (25:296). According to the authors, pore pressures subsequently recorded at a given water level have been relatively constant during different years (25:296). For data analysis, a flow net was calculated for a well-instrumented section with the finite element method, using the piezometric data (25:294-6). Utilizing additional information on seepage flow from a system of blanket and pipe drains and assuming ratios of horizontal to vertical permeability, permeabilities of the material were calculated via the finite element method and compared with permeability values determined from laboratory testing (25:296).

Widman and Stauble (59) present an assessment of data from deformations and pore pressures in the foundation of the 131 m high Austrian Schlegeis Arch Dam. The foundation rock at this project was reported to be a gneiss with some intercalations (interstratified beds) of soft schists (59:205). Piezometers were set upstream and downstream of a grout curtain at depths of 10, 20 and 30 m at the same location and at the downstream toe of the dam (59:207). The authors present a flow net based on the assumption of homogeneity and using the piezometer records.

For this model, flow through a grout curtain was represented by a series of closely spaced equipotential lines parallel to the axis of the curtain (59:208). Flow potential was represented as a percentage of available reservoir head dissipated. Flow nets were fitted to two sections by constructing equipotential contours from potential values plotted at the instrument locations. The analysis indicated that uplift pressures downstream of the grout curtain were considerably reduced by the structure, while little dissipation of hydrostatic pressure had occurred upstream (59:208).

Dibiagio et al. (2) present an evaluation of piezometric data in an assessment of the Norwegian Svartevann Dam. Piezometers were used to monitor the moraine till core of this 129 m high earth-rockfill structure (2:790). The authors present a qualitative evaluation of the data from time plots of measured hydraulic head vs. reservoir elevation data and note that, after first filling, pore pressures have become smaller with each cycle of reservoir filling (2:804).

The use of statistics in the interpretation of monitoring data is found in a recent Russian analysis. Epifanov et al. (9) present a statistical analysis of piezometric data from the Krasnoyarsk Dam. At this project, a network of 182 piezometers monitor a grout curtain and other portions of the foundation (9:425). The foundation monitored is a strongly jointed granite with shear zones of tectonic origin (9:425). Over 5 years of data were processed statistically. Correlation coefficients for piezometric head vs time and piezometric head vs reservoir elevation were generated and discussed. According to the authors,

relations between the established correlations and the structure of the foundation in individual sections were apparent (9:426).

#### IV. DATA ANALYSIS

In this section, an analysis of the Tellico piezometric data is presented. The procedures and methods used must necessarily be consistent with the purpose of monitoring, field conditions at the project, and applicable theory, as summarized in the preceding chapters. Also, as discussed in the introduction, the following analysis is to support the thesis--that statistical methods can be used along with deterministic analyses to yield important information about the seepage field. Steady flow equations and Darcian assumptions are used to formulate regression models and construct flow nets. The appropriateness of this approach will be evaluated in view of the results obtained and the context of the research.

##### IV.1 Data Assimilation

The subject piezometric data were placed on a computer database as part of a TVA pilot project to automate initial processing and archival of monitoring data. Piezometric data for the period June 1980 through February 1985 were provided by design engineers and consisted of monthly observations of hydraulic head computed from pressure readings and instrument elevations with Equ. 7. In order to differentiate between actual hydraulic head and observed elevations, TVA engineers refer to the observed values as "reading elevations." This nomenclature is therefore used for the piezometric data. These data were keyed into TVA's mainframe computer by data entry personnel and placed in a

Statistical Analysis System (SAS) database to support TVA data processing functions and to assist in this analysis. SAS is a comprehensive data management/analysis software package featuring advanced statistical capabilities.

A second SAS database containing daily headwater and tailwater values for the time period June 1980 through February 1985 was created to supplement the analysis. These data were obtained from TVA's Reservoir Operations Branch in several formats and consist of daily midnight elevations from the Tellico Dam headwater and Fort Loudon Dam tailwater gages.

The subject SAS databases can be conceptualized as rectangular blocks of data structured into observations and variables. For the piezometric data, the variables correspond to individual piezometers, while an observation corresponds to all data collected at the site during a given sampling event.

In order to search for causal relationships and to facilitate statistical analyses, a series of headwater-tailwater variables were created and added to the piezometric database. Values of headwater recorded at the time of pneumatic piezometer observation were first added. Next, a series of variables representing time averages of headwater/tailwater values assumed or estimated to exist prior to piezometer observation were computed and added to the database. A description of the headwater and tailwater variables are provided in Tables 1 and 2 respectively. The following schematic illustrates the definition of a 3-day antecedent time-average:

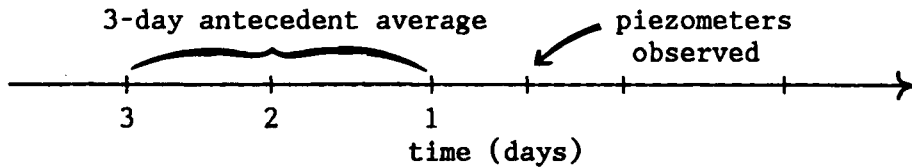
TABLE 1. DESCRIPTION OF HEADWATER VARIABLES

| VARIABLE | DESCRIPTION                                                                                                  |
|----------|--------------------------------------------------------------------------------------------------------------|
| HW       | - Headwater elevation recorded by field personnel on the day pneumatic piezometers were observed.            |
| HWAVG3   | - Average of midnight headwater elevations for 3 consecutive days prior to piezometer observation.           |
| HWAVG5   | - Average of midnight headwater elevations for 5 consecutive days prior to piezometer observation.           |
| HWAVG10  | - Average of midnight headwater elevations for 10 consecutive days prior to piezometer observation.          |
| HWAVG30  | - Average of midnight headwater elevations for 30 consecutive days prior to piezometer observation.          |
| HW4TO6   | - Average of midnight headwater elevations for the 4th, 5th and 6th days prior to piezometer observation.    |
| HW7TO9   | - Average of midnight headwater elevations for the 7th, 8th and 9th days prior to piezometer observation.    |
| HW10TO12 | - Average of midnight headwater elevations for the 10th, 11th and 12th days prior to piezometer observation. |

TABLE 2. DESCRIPTION OF TAILWATER VARIABLES

| VARIABLE | DESCRIPTION <sup>a</sup>                                                                                     |
|----------|--------------------------------------------------------------------------------------------------------------|
| TWAVG3   | - Average of midnight tailwater elevations for 3 consecutive days prior to piezometer observation.           |
| TWAVG5   | - Average of midnight tailwater elevations for 5 consecutive days prior to piezometer observation.           |
| TWAVG10  | - Average of midnight tailwater elevations for 10 consecutive days prior to piezometer observation.          |
| TWAVG30  | - Average of midnight tailwater elevations for 30 consecutive days prior to piezometer observation.          |
| TW4TO6   | - Average of midnight tailwater elevations for the 4th, 5th and 6th days prior to piezometer observation.    |
| TW7TO9   | - Average of midnight tailwater elevations for the 7th, 8th and 9th days prior to piezometer observation.    |
| TW10TO12 | - Average of midnight tailwater elevations for the 10th, 11th and 12th days prior to piezometer observation. |

<sup>a</sup>Tailwater elevations from Fort Loudon Dam Tailwater Gage.



The headwater/tailwater variables (referred to hereafter as HW/TW variables) presented represent a simplification of time-fluctuations of reservoir elevations, created for comparison with recorded piezometric heads and for use in steady-flow equations.

For this research, data analysis is accomplished primarily on a microcomputer to minimize costs and provide greater flexibility. Both the subject SAS databases were copied to microcomputer data files. BASIC language programs were then written as needed to analyze and report the data. The results were then spot-checked with SAS on the TVA mainframe.

#### IV.2 Presentation of Data

Summary statistics for piezometers and HW/TW variables are presented in Tables 3 and 4, respectively. Included are maximum observed values and date of occurrence, minimum values and date of occurrence, means, ranges, and instrument elevations. The location of the piezometers and identification system (Plate 3) was presented in Section II.6.1.

Plots of daily midnight headwater and tailwater elevations for the period of analysis are shown in Figures 10 and 11, respectively.

TABLE 3. SUMMARY STATISTICS FOR PIEZOMETER DATA

| PIEZOMETER | MAXIMUM<br>HEAD<br>(ft) | DATE OF<br>MAXIMUM<br>(y/m/d) | MINIMUM<br>HEAD<br>(ft) | DATE OF<br>MINIMUM<br>(y/m/d) | MEAN<br>HEAD<br>(ft) | NUMBER<br>OF<br>READINGS | RANGE<br>IN HEAD<br>(ft) | INSTRUMENT<br>ELEVATION<br>(ft) |
|------------|-------------------------|-------------------------------|-------------------------|-------------------------------|----------------------|--------------------------|--------------------------|---------------------------------|
| AU-1       | 802.4                   | 80/06/19                      | 789.8                   | 83/02/17                      | 796.49               | 59                       | 12.6                     | 674.0                           |
| AU-2       | 807.1                   | 84/05/11                      | 795.6                   | 81/01/19                      | 802.71               | 59                       | 11.5                     | 707.9                           |
| AU-3       | 814.7                   | 81/05/19                      | 806.0                   | 82/01/25                      | 809.92               | 59                       | 8.7                      | 727.5                           |
| AE         | 799.0                   | 83/06/22                      | 784.9                   | 84/04/25                      | 794.39               | 59                       | 14.1                     | 718.2                           |
| AD-1       | 749.6                   | 84/05/11                      | 736.7                   | 85/01/25                      | 741.14               | 59                       | 12.9                     | 675.5                           |
| AD-2       | 748.0                   | 84/05/11                      | 735.8                   | 85/01/25                      | 740.18               | 59                       | 12.2                     | 715.0                           |
| AD-3       | 755.9                   | 83/01/26                      | 735.3                   | 85/01/25                      | 739.99               | 59                       | 20.6                     | 730.7                           |
| AD-4       | 749.0                   | 84/05/11                      | 729.9                   | 83/01/26                      | 739.59               | 59                       | 19.1                     | 674.5                           |
| AD-5       | 746.7                   | 84/05/11                      | 733.5                   | 85/01/25                      | 737.33               | 59                       | 13.2                     | 710.9                           |
| AD-6       | 748.0                   | 84/05/11                      | 735.5                   | 85/01/25                      | 738.99               | 58                       | 12.5                     | 731.6                           |
|            |                         |                               |                         |                               |                      |                          |                          |                                 |
| BU-1       | 763.9                   | 84/05/11                      | 754.2                   | 81/12/17                      | 758.37               | 59                       | 9.7                      | 682.7                           |
| BU-2       | 790.0                   | 81/05/19                      | 780.2                   | 80/07/14                      | 784.77               | 59                       | 9.8                      | 715.2                           |
| BU-3       | 812.7                   | 84/08/20                      | 802.6                   | 81/12/17                      | 808.07               | 59                       | 10.1                     | 734.5                           |
| BE         | 796.4                   | 83/08/25                      | 789.5                   | 85/02/20                      | 793.45               | 59                       | 6.9                      | 731.8                           |
| BD-1       | 750.9                   | 84/05/11                      | 740.5                   | 85/01/25                      | 743.98               | 59                       | 10.4                     | 678.4                           |
| BD-2       | 753.7                   | 83/02/17                      | 739.1                   | 85/01/25                      | 744.04               | 59                       | 14.6                     | 713.5                           |
| BD-3       | 744.5                   | 84/05/11                      | 734.6                   | 85/01/25                      | 738.03               | 59                       | 9.9                      | 730.0                           |
| BD-4       | 749.7                   | 84/08/20                      | 735.9                   | 81/01/19                      | 739.85               | 59                       | 13.8                     | 682.8                           |
| BD-5       | 749.4                   | 84/05/11                      | 736.1                   | 85/01/25                      | 740.35               | 59                       | 13.3                     | 705.6                           |
| BD-6       | 745.9                   | 84/05/11                      | 736.2                   | 85/01/25                      | 739.33               | 59                       | 9.7                      | 729.7                           |
|            |                         |                               |                         |                               |                      |                          |                          |                                 |
| CU-1       | 811.9                   | 83/04/25                      | 799.4                   | 82/02/17                      | 806.41               | 59                       | 12.5                     | 676.9                           |
| CU-2       | 813.9                   | 82/07/22                      | 800.5                   | 81/12/17                      | 806.74               | 59                       | 13.4                     | 712.6                           |
| CU-3       | 821.3                   | 82/02/17                      | 804.9                   | 82/01/25                      | 809.19               | 59                       | 16.4                     | 731.3                           |
| CE         | 805.9                   | 82/02/17                      | 788.6                   | 80/08/14                      | 794.43               | 59                       | 17.3                     | 732.1                           |
| CD-1       | 745.5                   | 83/05/25                      | 736.5                   | 85/01/25                      | 740.76               | 59                       | 9.0                      | 674.0                           |
| CD-2       | 752.2                   | 84/05/11                      | 734.4                   | 83/09/20                      | 740.14               | 59                       | 17.8                     | 708.6                           |
| CD-3       | 751.9                   | 84/05/11                      | 736.9                   | 81/01/19                      | 740.86               | 59                       | 15.0                     | 733.4                           |
| CD-4       | 750.9                   | 84/05/11                      | 735.4                   | 81/02/23                      | 739.79               | 59                       | 15.5                     | 674.7                           |
| CD-5       | 747.8                   | 84/05/11                      | 732.6                   | 83/01/26                      | 738.08               | 59                       | 15.2                     | 713.4                           |
| CD-6       | 748.8                   | 84/05/11                      | 735.0                   | 81/02/23                      | 739.22               | 59                       | 13.8                     | 731.5                           |
|            |                         |                               |                         |                               |                      |                          |                          |                                 |
| DU-1       | 807.4                   | 83/09/20                      | 794.7                   | 82/12/27                      | 800.90               | 59                       | 12.7                     | 679.3                           |
| DU-2       | 812.3                   | 83/06/22                      | 798.5                   | 82/11/22                      | 805.37               | 59                       | 13.8                     | 720.5                           |
| DD-1       | 751.5                   | 84/05/11                      | 735.8                   | 85/01/25                      | 740.39               | 59                       | 15.7                     | 673.5                           |
| DD-2       | 750.7                   | 84/05/11                      | 734.8                   | 84/12/20                      | 739.06               | 59                       | 15.9                     | 706.6                           |
| DD-4       | 748.7                   | 84/05/11                      | 734.2                   | 81/02/23                      | 737.98               | 59                       | 14.5                     | 667.7                           |
| DD-5       | 741.5                   | 83/05/25                      | 707.8                   | 85/01/25                      | 734.87               | 59                       | 33.7                     | 702.5                           |

TABLE 3 (CONTINUED)

| PIEZOMETER | MAXIMUM<br>HEAD<br>(ft) | DATE OF<br>MAXIMUM<br>(y/m/d) | MINIMUM<br>HEAD<br>(ft) | DATE OF<br>MINIMUM<br>(y/m/d) | MEAN<br>HEAD<br>(ft) | NUMBER<br>OF<br>READINGS | RANGE<br>IN HEAD<br>(ft) | INSTRUMENT<br>ELEVATION<br>(ft) |
|------------|-------------------------|-------------------------------|-------------------------|-------------------------------|----------------------|--------------------------|--------------------------|---------------------------------|
| EU-1       | 813.3                   | 84/08/20                      | 792.0                   | 81/12/17                      | 806.19               | 59                       | 21.3                     | 718.2                           |
| EU-2       | 813.9                   | 83/06/22                      | 804.7                   | 82/01/25                      | 808.77               | 59                       | 9.2                      | 747.0                           |
| EU-3       | 813.8                   | 84/08/20                      | 805.2                   | 82/01/25                      | 809.81               | 58                       | 8.6                      | 766.0                           |
| EE         | 797.2                   | 83/10/19                      | 791.9                   | 82/03/17                      | 794.70               | 59                       | 5.3                      | 769.3                           |
| ED-1       | 753.2                   | 84/05/11                      | 740.5                   | 81/01/19                      | 744.39               | 59                       | 12.7                     | 708.2                           |
| ED-2       | 789.8                   | 83/06/22                      | 781.4                   | 82/02/17                      | 786.50               | 59                       | 8.4                      | 743.6                           |
| ED-3       | 793.7                   | 83/06/22                      | 785.8                   | 81/12/17                      | 790.01               | 59                       | 7.9                      | 758.1                           |
| ED-4       | 747.9                   | 84/05/11                      | 732.4                   | 84/02/24                      | 740.95               | 59                       | 15.5                     | 687.4                           |
| ED-5       | 752.3                   | 84/05/11                      | 727.6                   | 83/09/20                      | 742.23               | 59                       | 24.7                     | 727.6                           |
| ED-6       | 782.8                   | 82/08/26                      | 779.6                   | 80/06/19                      | 779.66               | 59                       | 3.2                      | 779.6                           |
| H-1        | 750.4                   | 84/05/11                      | 738.0                   | 81/03/18                      | 741.25               | 58                       | 12.4                     | 730.53                          |
| H-2        | 749.8                   | 84/05/11                      | 738.4                   | 81/03/18                      | 741.53               | 57                       | 11.4                     | 731.68                          |
| H-3        | 746.3                   | 84/05/11                      | 738.3                   | 81/03/18                      | 741.48               | 57                       | 8.0                      | 731.58                          |
| H-4        | 746.8                   | 84/05/11                      | 738.3                   | 81/03/18                      | 741.48               | 57                       | 8.5                      | 728.15                          |
| H-5        | 746.5                   | 84/05/11                      | 737.2                   | 80/12/16                      | 741.20               | 56                       | 9.3                      | 725.30                          |
| H-6        | 747.8                   | 84/05/11                      | 736.8                   | 83/09/20                      | 741.23               | 58                       | 11.0                     | 725.00                          |
| H-7        | 746.8                   | 84/05/11                      | 738.0                   | 81/03/18                      | 741.33               | 58                       | 8.8                      | 731.18                          |
| H-8        | 751.6                   | 84/05/11                      | 737.4                   | 81/01/19                      | 741.00               | 58                       | 14.2                     | 730.48                          |
| H-8A       | 751.4                   | 84/05/11                      | 737.3                   | 85/01/25                      | 741.08               | 58                       | 14.1                     | 728.02                          |
| H-9        | 751.9                   | 84/05/11                      | 737.0                   | 85/01/25                      | 740.93               | 58                       | 14.9                     | 730.21                          |
| H-10       | 752.0                   | 84/05/11                      | 737.0                   | 85/01/25                      | 741.01               | 58                       | 15.0                     | 729.06                          |
| H-11       | 752.0                   | 84/05/11                      | 737.3                   | 85/01/25                      | 740.98               | 58                       | 14.7                     | 729.96                          |
| H-12       | 751.9                   | 84/05/11                      | 737.2                   | 85/01/25                      | 740.91               | 58                       | 14.7                     | 731.56                          |
| H-13       | 752.1                   | 84/05/11                      | 737.0                   | 85/01/25                      | 740.84               | 58                       | 15.1                     | 729.34                          |
| H-14       | 752.2                   | 84/05/11                      | 737.1                   | 85/01/25                      | 740.96               | 58                       | 15.1                     | 729.63                          |
| H-15       | 752.3                   | 84/05/11                      | 737.0                   | 85/01/25                      | 740.99               | 58                       | 15.3                     | 727.41                          |
| H-16       | 752.4                   | 84/05/11                      | 735.4                   | 85/01/25                      | 740.94               | 58                       | 17.0                     | 726.34                          |
| H-17       | 752.4                   | 84/05/11                      | 737.2                   | 85/01/25                      | 741.10               | 58                       | 15.2                     | 718.37                          |
| H-18       | 752.4                   | 84/05/11                      | 737.1                   | 85/01/25                      | 741.21               | 58                       | 15.3                     | 714.97                          |
| H-19       | 752.6                   | 84/05/11                      | 737.7                   | 81/03/18                      | 741.31               | 58                       | 14.9                     | 720.65                          |
| H-20       | 752.6                   | 84/05/11                      | 737.4                   | 85/01/25                      | 741.34               | 58                       | 15.2                     | 722.83                          |
| H-21       | 753.0                   | 84/05/11                      | 738.3                   | 81/01/19                      | 742.12               | 58                       | 14.7                     | 732.62                          |
| H-22       | 755.0                   | 84/05/11                      | 740.3                   | 83/12/23                      | 746.10               | 58                       | 14.7                     | 740.04                          |
| H-23       | 754.7                   | 84/05/11                      | 735.4                   | 83/09/20                      | 745.05               | 2                        | 19.3                     | 747.64                          |
| H-24       | 755.5                   | 80/08/14                      | 755.2                   | 80/09/22                      | 755.30               | 3                        | 0.3                      | 758.28                          |
| H-25       | 756.2                   | 84/05/11                      | 744.2                   | 83/12/23                      | 747.99               | 30                       | 12.0                     | 744.71                          |

TABLE 4. SUMMARY STATISTICS FOR HEADWATER/TAIWATER VARIABLES

| VARIABLE | MAXIMUM<br>ELEVATION<br>(ft) | DATE OF<br>MAXIMUM<br>(y/m/d) | MINIMUM<br>ELEVATION<br>(ft) | DATE OF<br>MINIMUM<br>(y/m/d) | MEAN<br>ELEVATION<br>(ft) | NUMBER<br>OF<br>VALUES | RANGE<br>IN ELEV.<br>(ft) |
|----------|------------------------------|-------------------------------|------------------------------|-------------------------------|---------------------------|------------------------|---------------------------|
| HW       | 814.25                       | 84/05/11                      | 807.50                       | 84/03/19                      | 810.90                    | 59                     | 6.75                      |
| HWAVG3   | 814.76                       | 84/05/11                      | 807.49                       | 83/02/17                      | 810.87                    | 59                     | 7.27                      |
| HWAVG5   | 814.55                       | 84/05/11                      | 807.62                       | 84/03/19                      | 810.87                    | 59                     | 6.93                      |
| HWAVG10  | 813.91                       | 84/05/11                      | 807.59                       | 84/03/19                      | 810.86                    | 59                     | 6.32                      |
| HWAVG30  | 813.18                       | 84/05/30                      | 807.79                       | 83/01/26                      | 810.88                    | 59                     | 5.39                      |
| HW4TO6   | 813.79                       | 84/05/11                      | 807.51                       | 83/12/23                      | 810.86                    | 59                     | 6.28                      |
| HW7TO9   | 813.51                       | 84/05/11                      | 807.54                       | 83/12/23                      | 810.85                    | 59                     | 5.97                      |
| HW10TO12 | 813.13                       | 81/06/16                      | 807.58                       | 85/01/25                      | 810.83                    | 59                     | 5.55                      |
| TWAVG3   | 755.81                       | 84/05/11                      | 734.97                       | 81/01/19                      | 739.76                    | 59                     | 20.84                     |
| TWAVG5   | 754.66                       | 84/05/11                      | 735.12                       | 81/01/19                      | 739.81                    | 59                     | 19.54                     |
| TWAVG10  | 748.83                       | 84/05/11                      | 735.18                       | 81/01/19                      | 739.84                    | 59                     | 13.65                     |
| TWAVG30  | 745.54                       | 84/05/30                      | 735.58                       | 81/03/18                      | 739.82                    | 59                     | 9.96                      |
| TW4TO6   | 749.85                       | 84/05/11                      | 735.23                       | 81/01/19                      | 739.95                    | 59                     | 14.62                     |
| TW7TO9   | 743.87                       | 82/02/17                      | 735.07                       | 81/01/19                      | 739.84                    | 59                     | 8.80                      |
| TW10TO12 | 743.77                       | 82/02/17                      | 735.20                       | 81/03/18                      | 739.65                    | 59                     | 8.57                      |

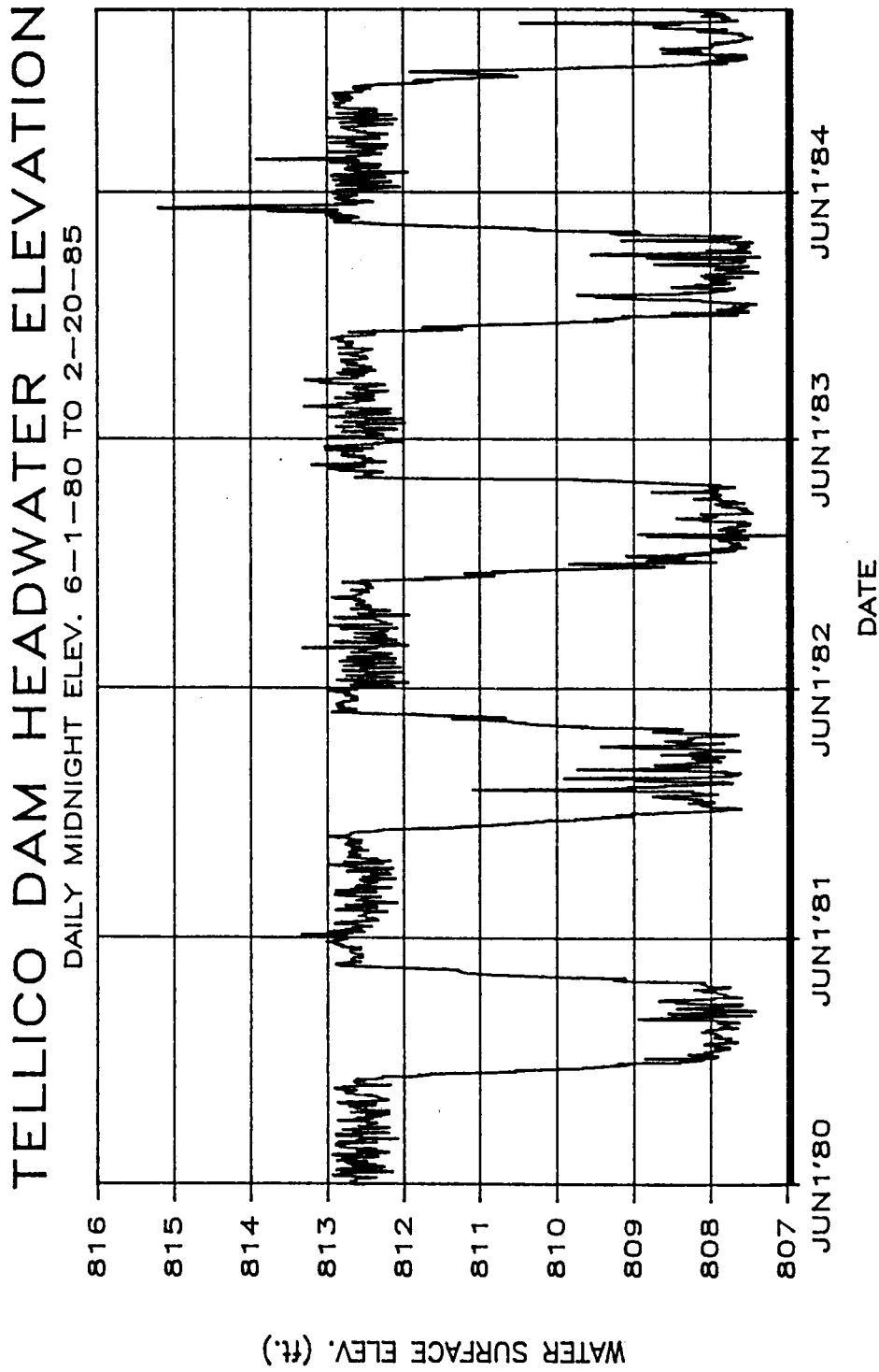


FIGURE 10. TELLICO DAM DAILY MIDNIGHT HEADWATER ELEVATIONS

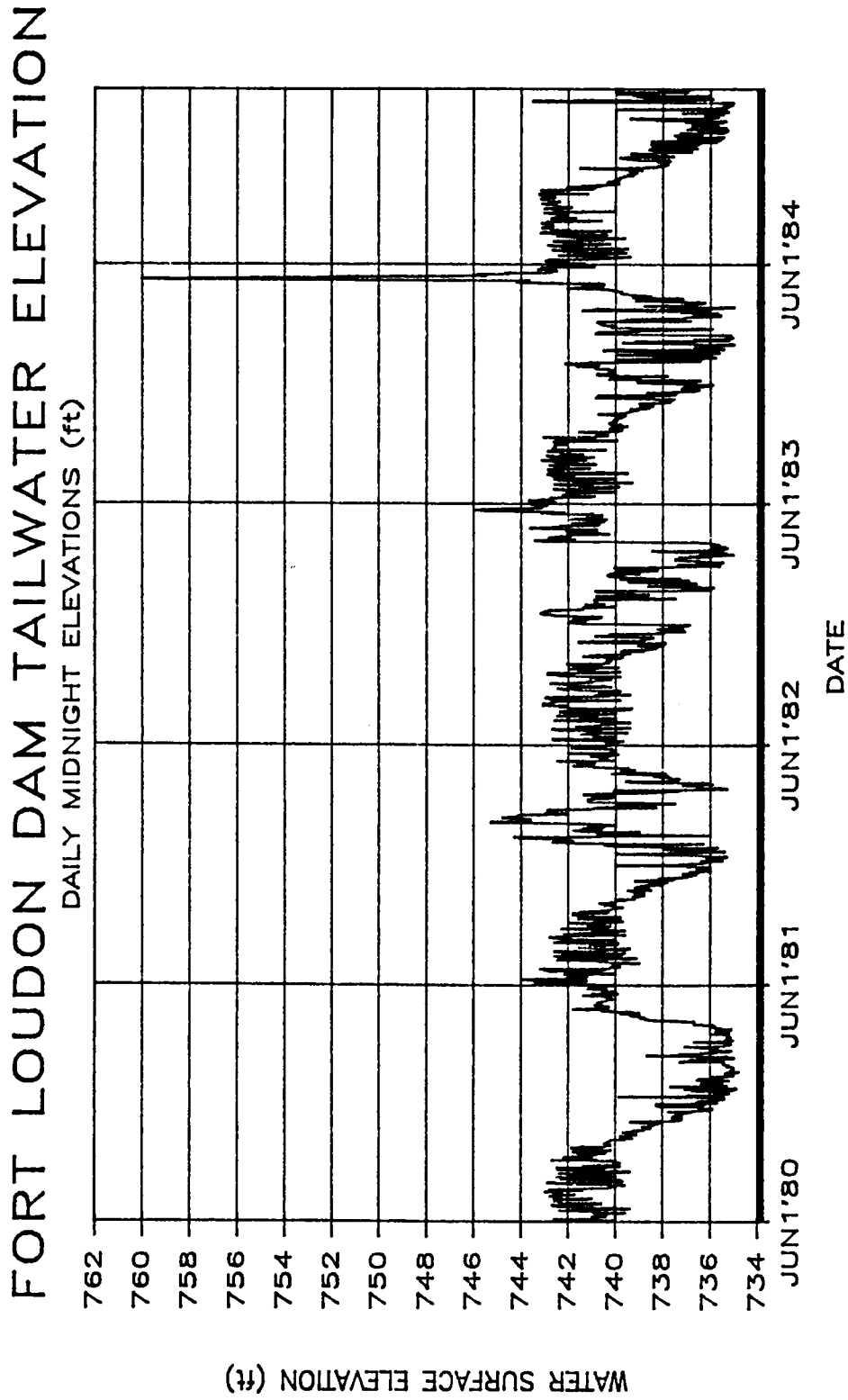


FIGURE 11. FORT LOUDON DAM DAILY MIDNIGHT TAILWATER ELEVATIONS

Histograms of piezometer reading elevations for the subject piezometers are presented in Figures 12-22. Observations are plotted equidistant on the time axis and connected by straight lines. Connection of the data points by lines is shown to project general trends and to aid in differentiating the sets of data points for the respective piezometers--it is not intended to imply that the observed data is continuous and can be extrapolated as such.

The standard observation frequency for the piezometers was monthly, with three exceptions. One special observation was made on September 27, 1982, following earth tremors in the area on September 24, 1982. A second special observation was made on February 1, 1984 following the discovery of the sinkhole now monitored by piezometer F-1s. A third special observation was made on May 11, 1984 subsequent to observed record headwater and tailwater elevations at the project.

Piezometers with similar locations in the five instrumented sections were plotted together for comparative purposes. For piezometers upstream of the grout curtain, headwater elevations measured prior to the time of observation (HW) were also plotted, while for piezometers downstream of the grout curtain, the three-day antecedent midnight tailwater average (TWAVG3) was plotted. This was done to show the response of the piezometric data to headwater and tailwater elevations.

As shown in Figures 10 and 11, both the Tellico Dam headwater elevations and Fort Loudon tailwater elevations show a cyclic seasonal pattern generally coincident with reservoir operating plans. These figures show that May 1984 flooding had a significant effect on

# PIEZOMETER READINGS AT POINT U-1

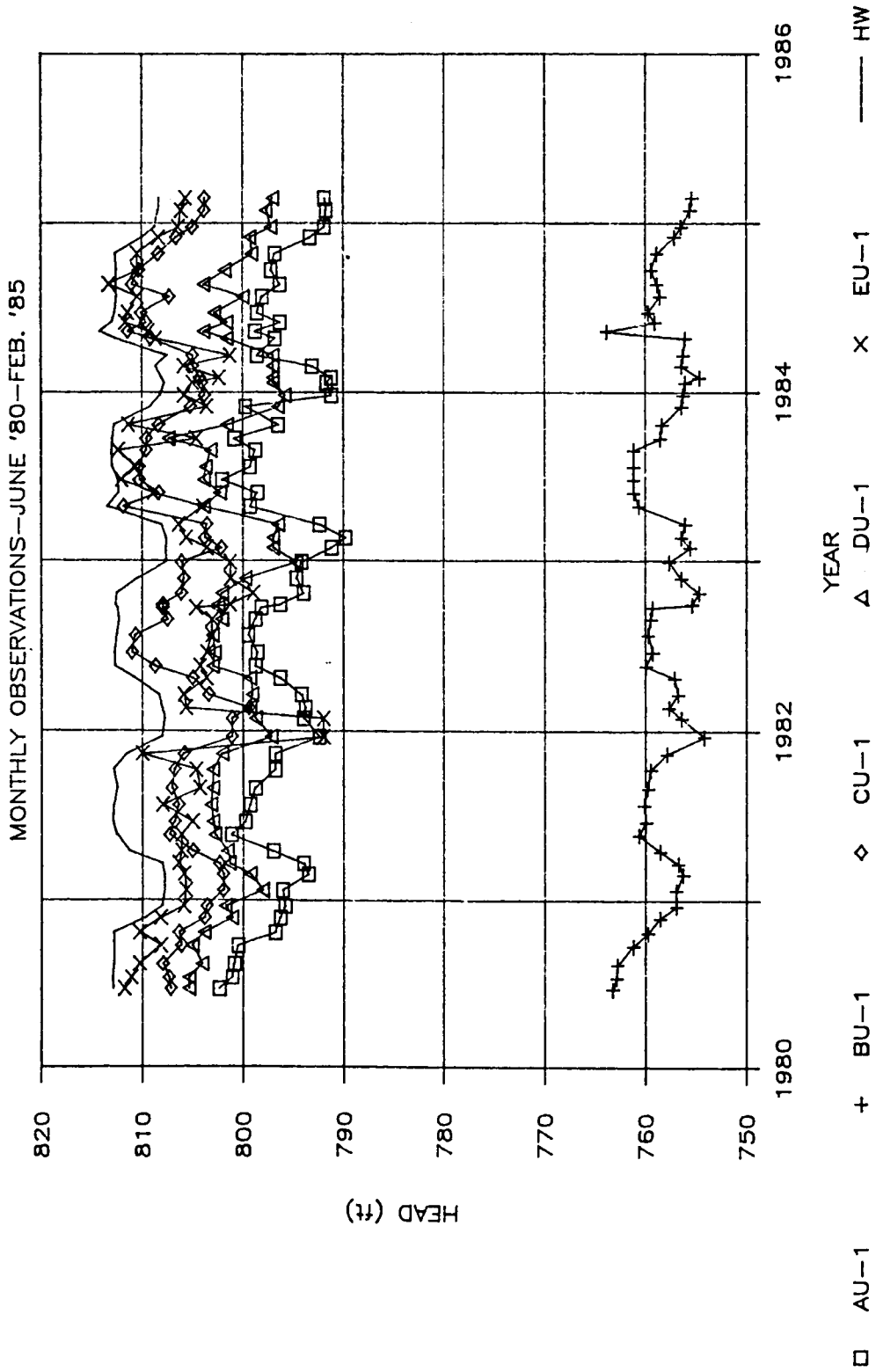


FIGURE 12. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT U-1

# PIEZOMETER READINGS AT POINT U-2

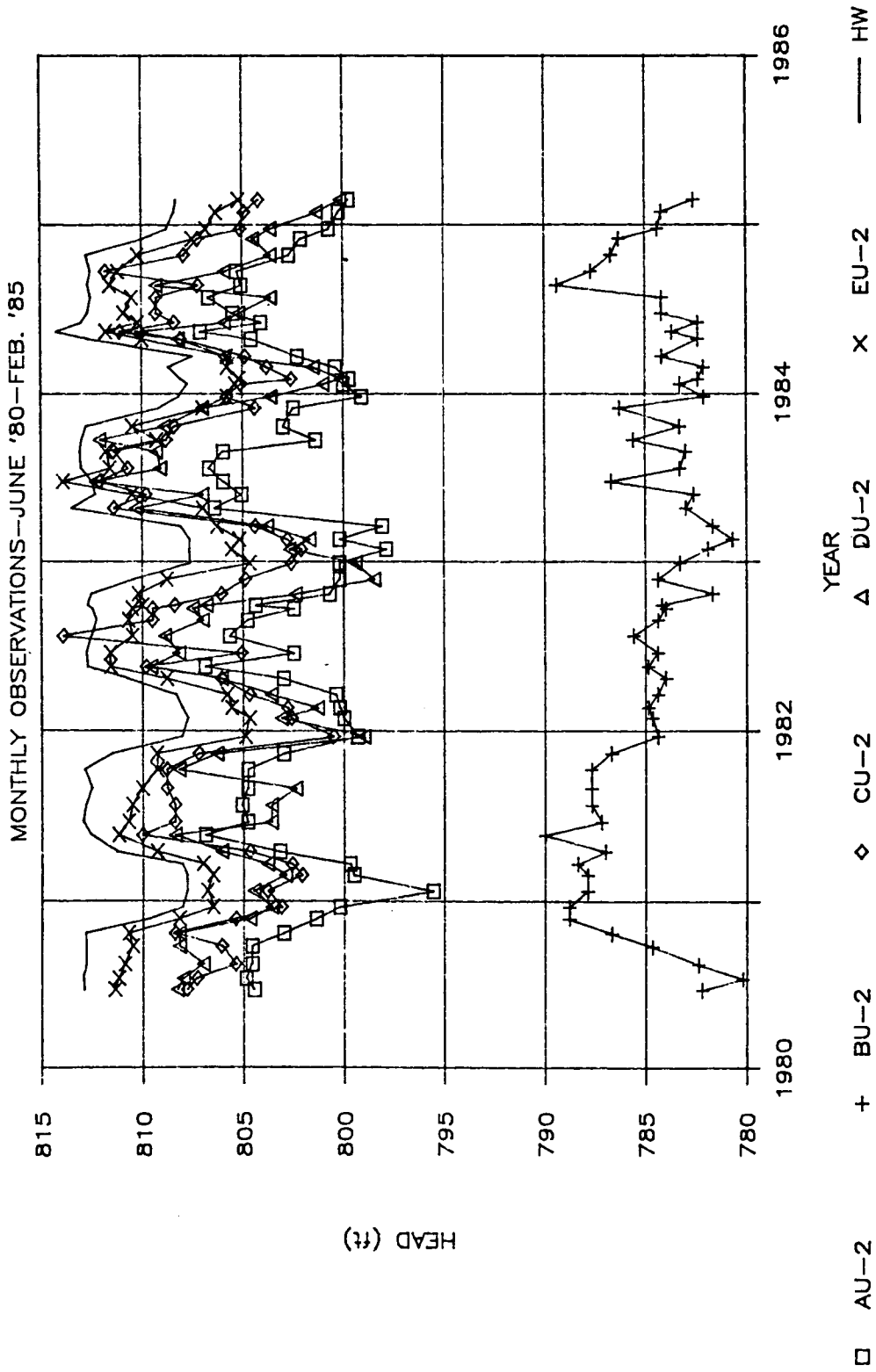


FIGURE 13. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT U-2

# PIEZOMETER READINGS AT POINT U-3

MONTHLY OBSERVATIONS—JUNE '80—FEB. '85

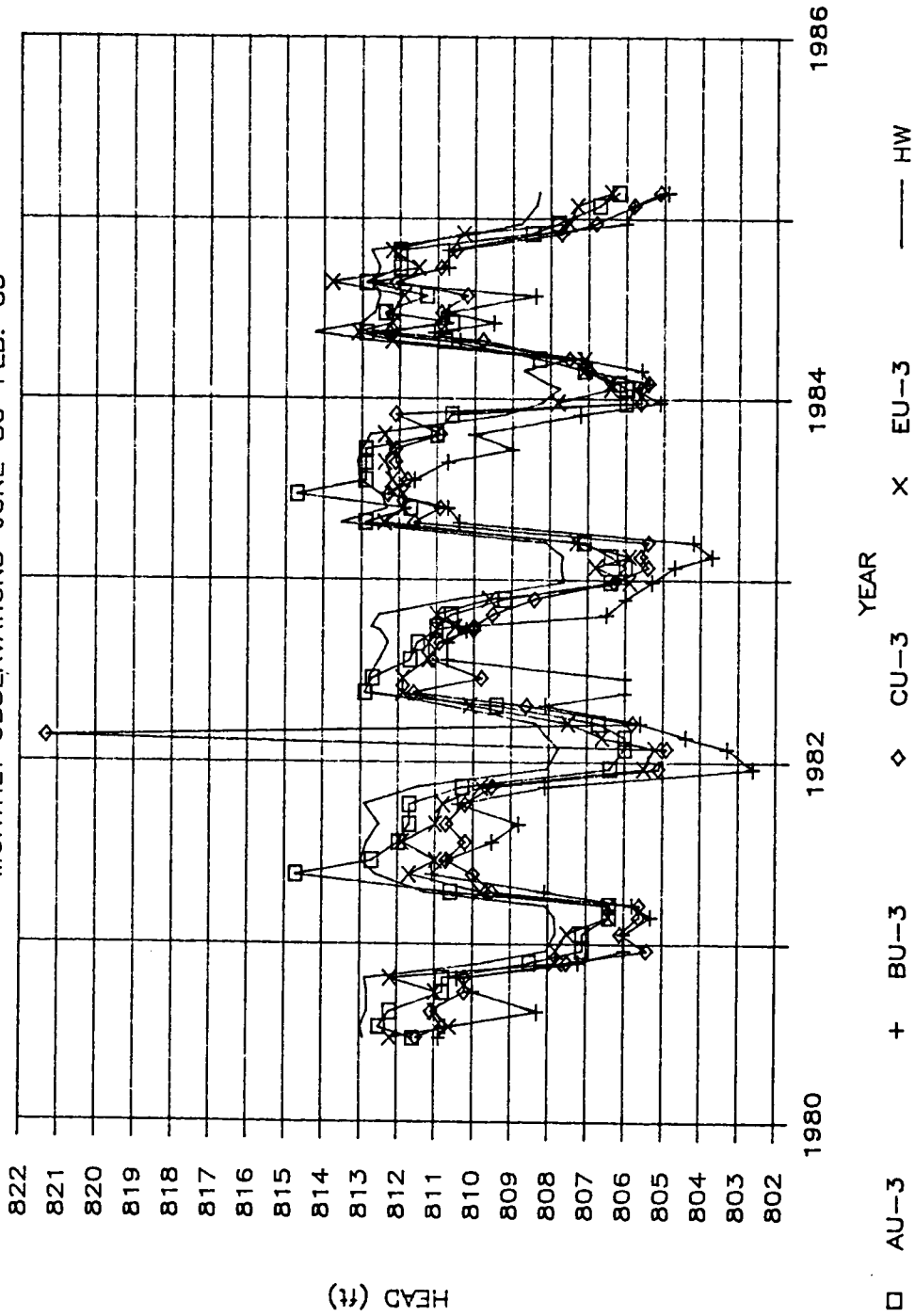


FIGURE 14. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT U-3

# PIEZOMETER READINGS AT POINT E

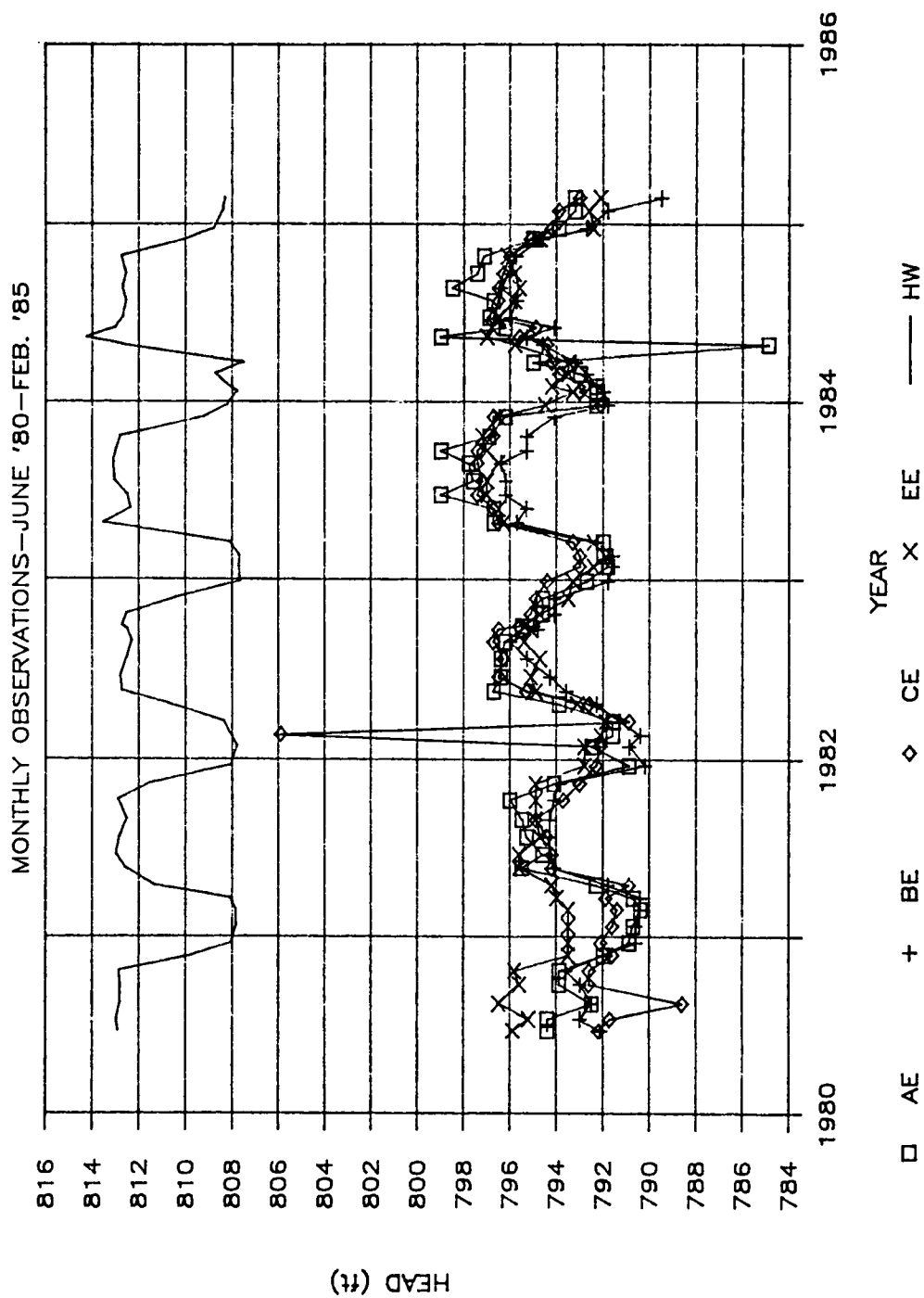


FIGURE 15. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT E

# PIEZOMETER READINGS AT POINT D-1

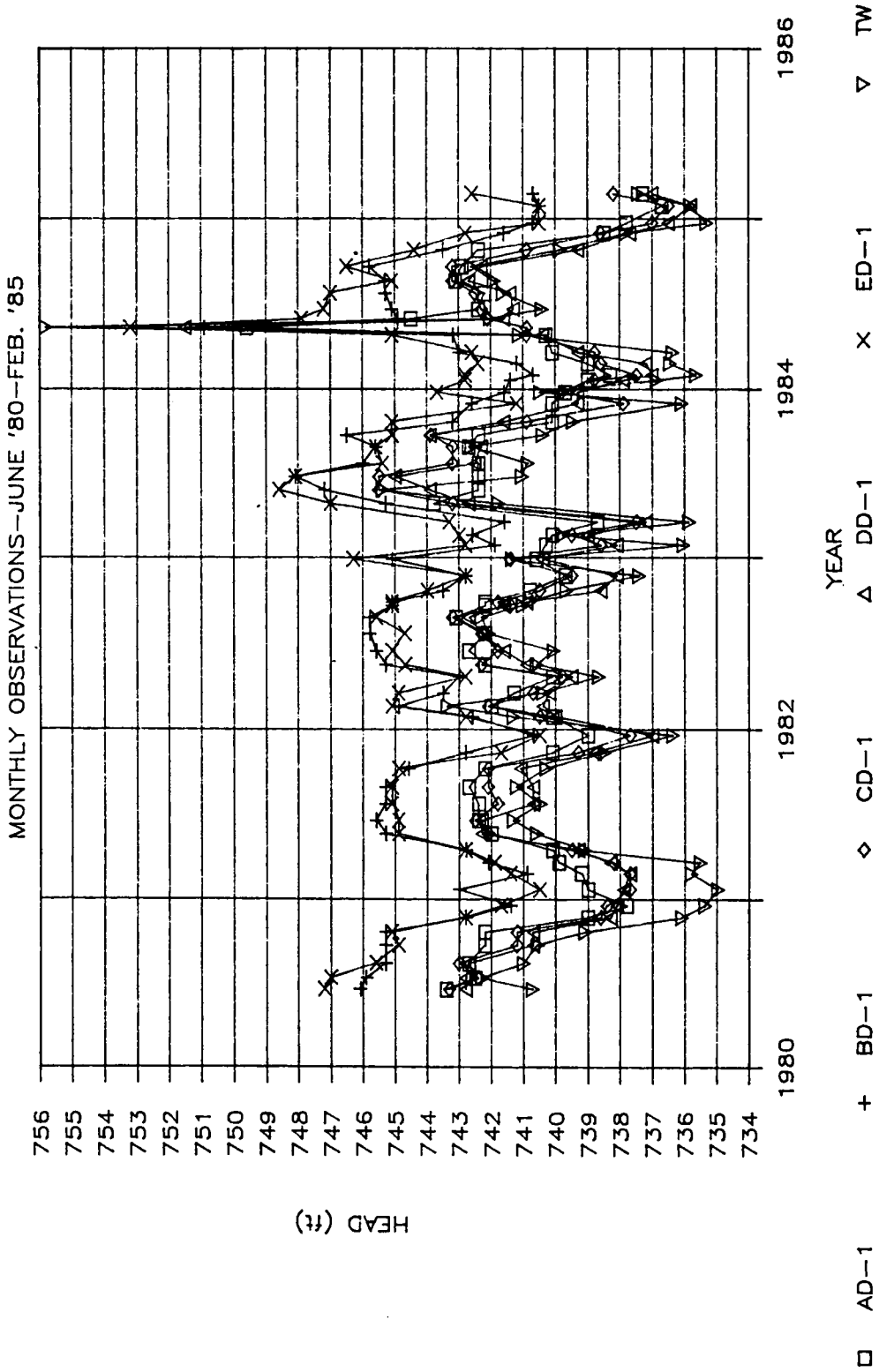


FIGURE 16. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT D-1

# PIEZOMETER READINGS AT POINT D-2

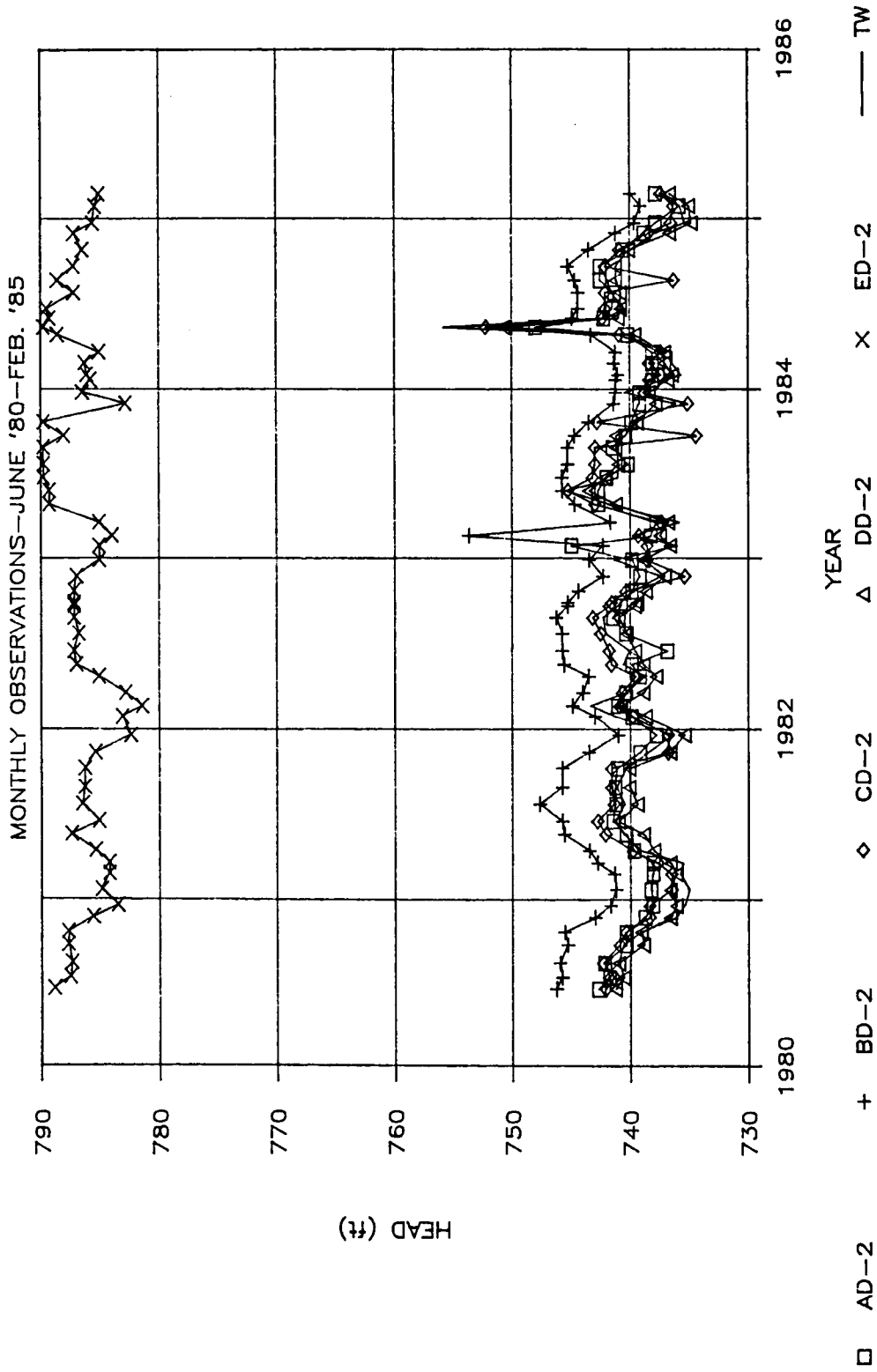


FIGURE 17. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT D-2

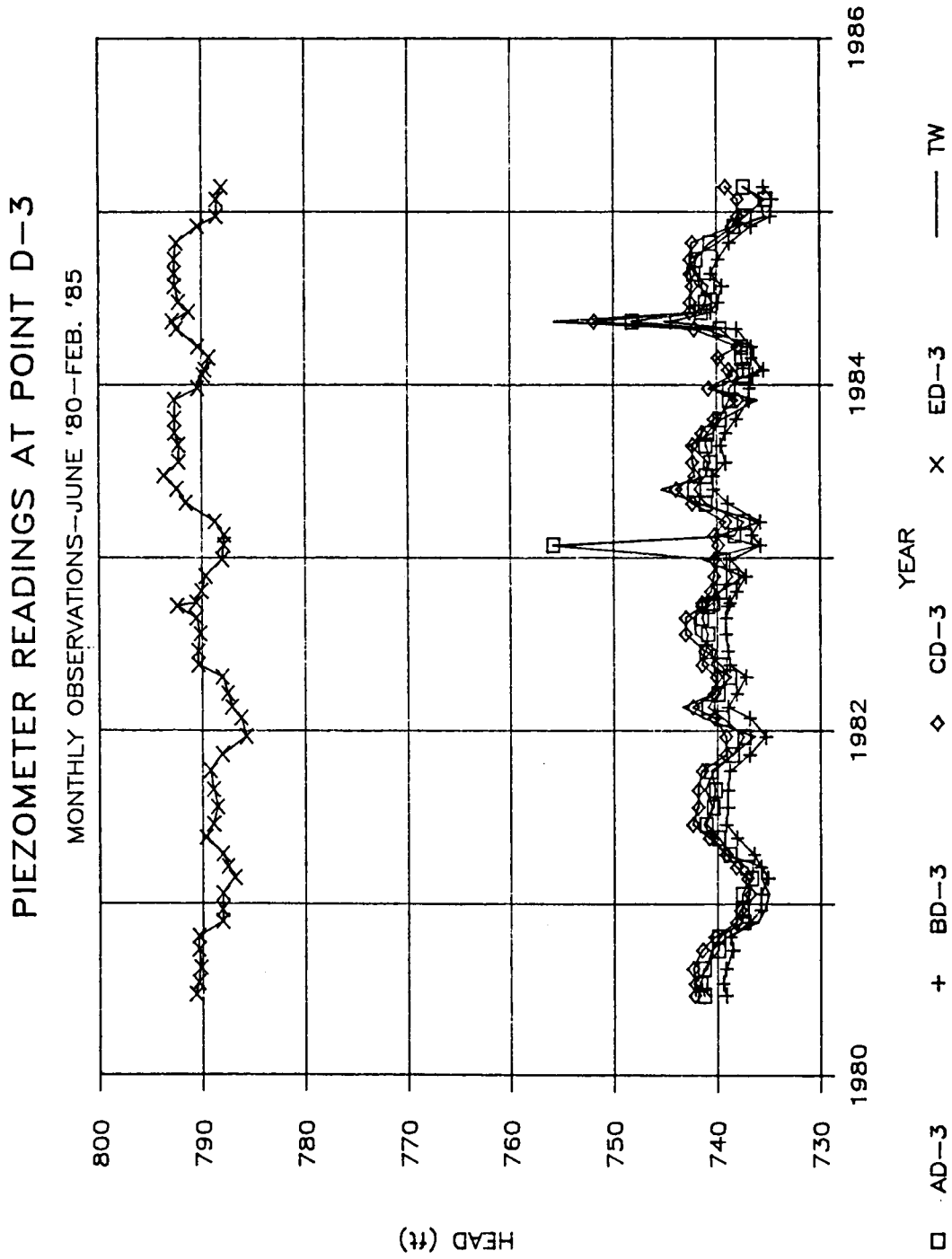


FIGURE 18. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT D-3

# PIEZOMETER READINGS AT POINT D-4

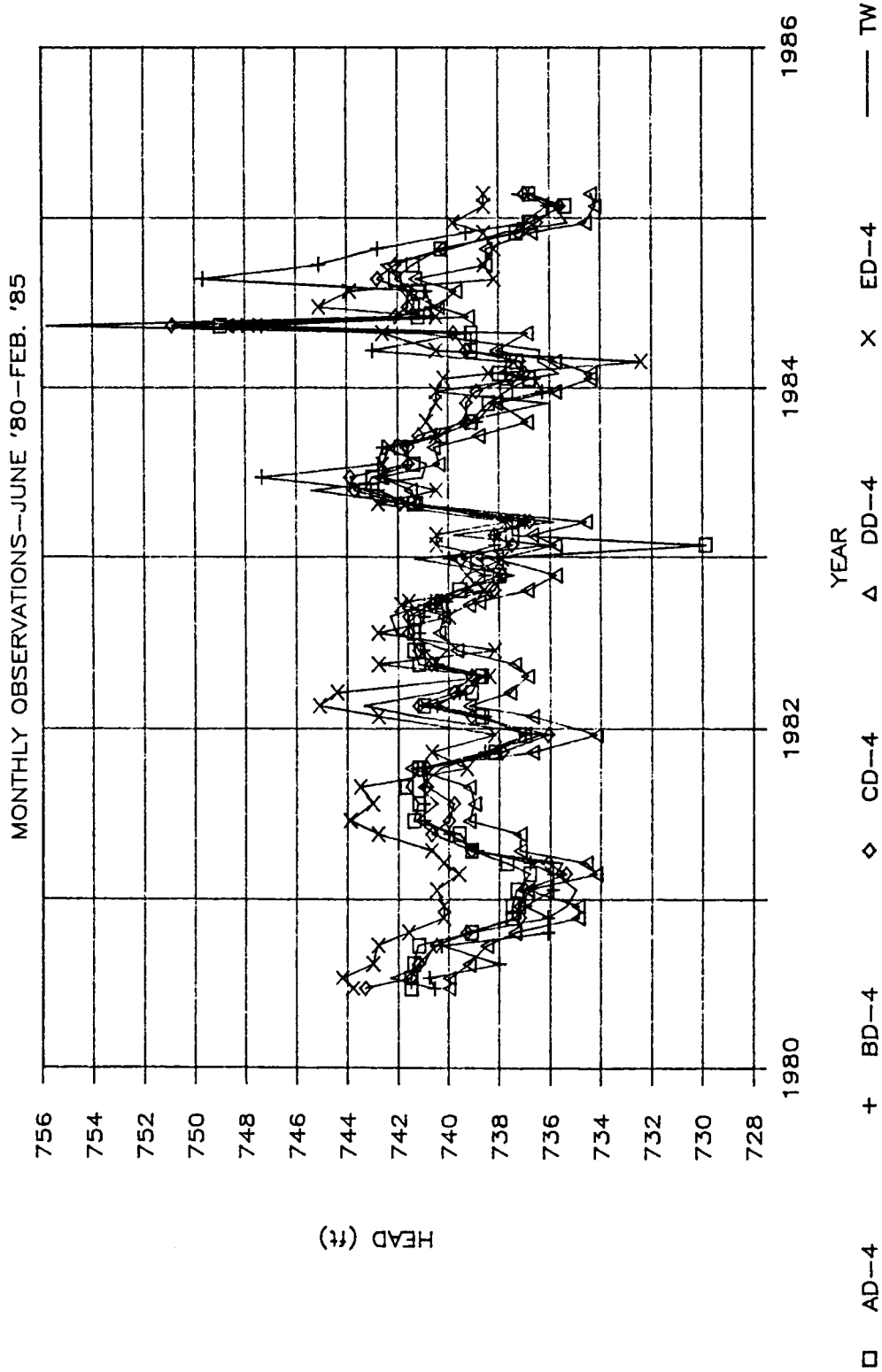


FIGURE 19. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT D-4

# PIEZOMETER READINGS AT POINT D-5

MONTHLY OBSERVATIONS—JUNE '80—FEB. '85

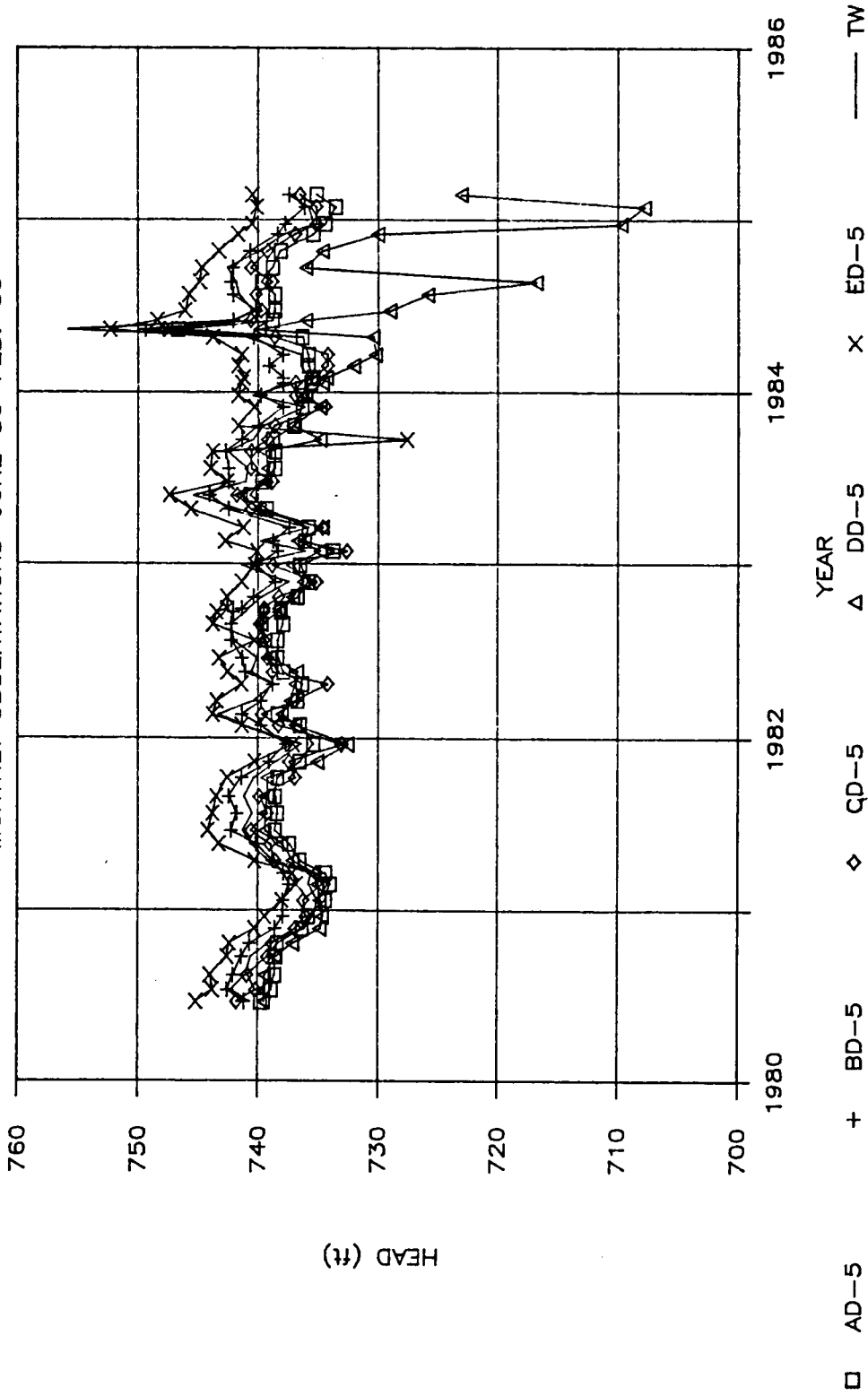


FIGURE 20. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT D-5

# PIEZOMETER READINGS AT POINT D-6

MONTHLY OBSERVATIONS--JUNE '80--FEB. '85

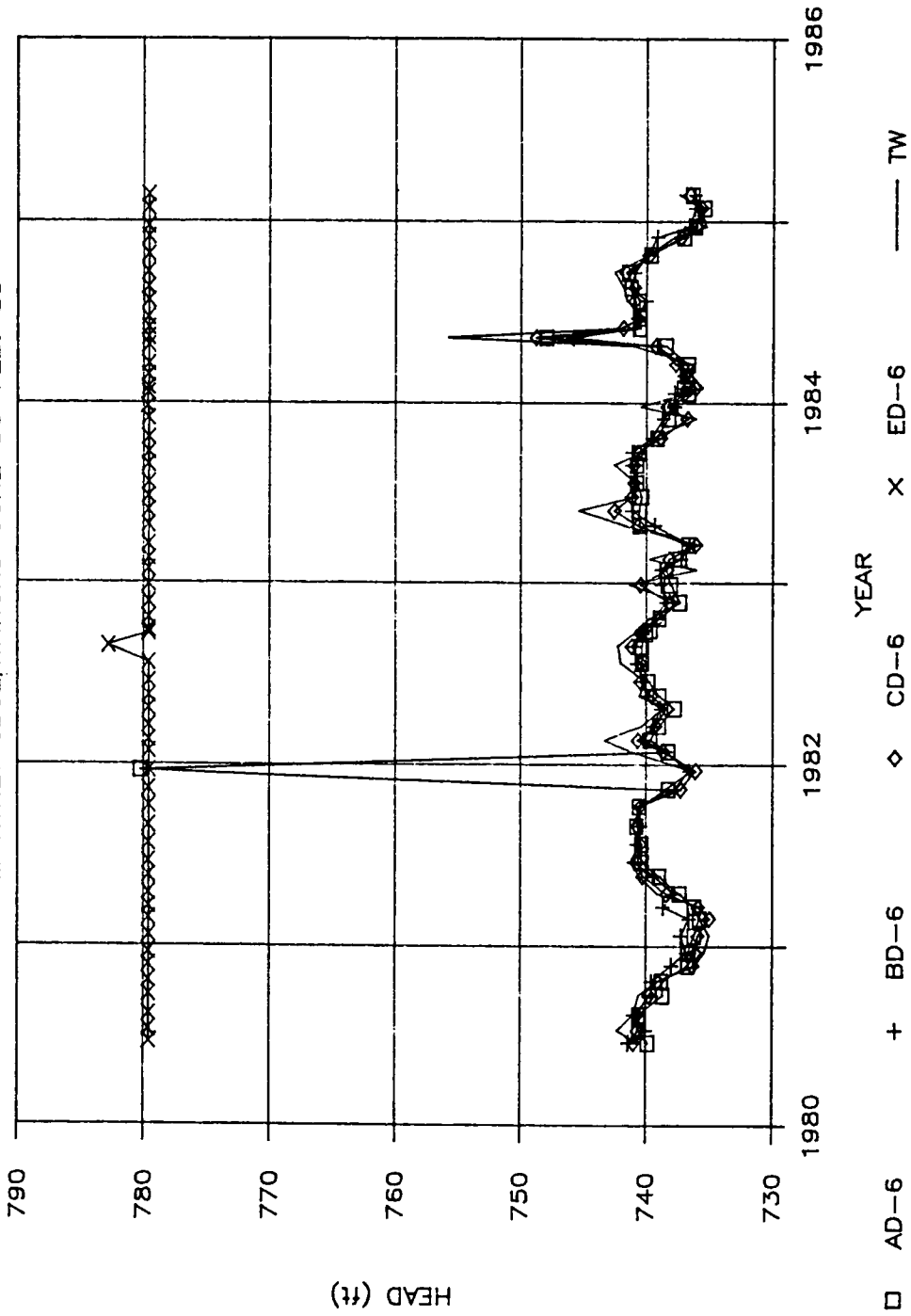


FIGURE 21. MONTHLY FOUNDATION PIEZOMETER READINGS AT POINT D-6

# PIEZOMETER READINGS FOR RANGE H

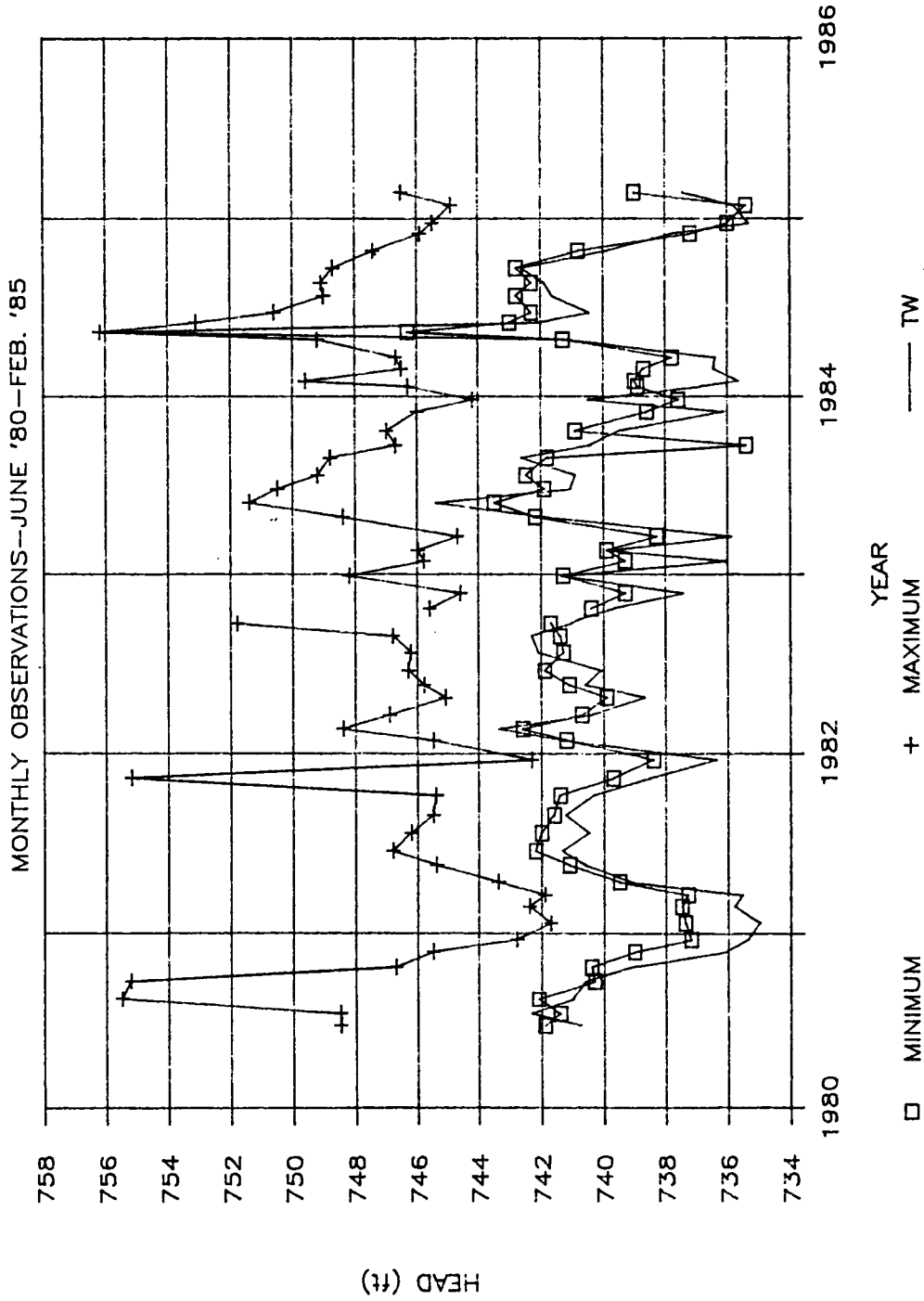


FIGURE 22. MONTHLY FOUNDATION PIEZOMETER READINGS FOR RANGE H

reservoir elevations, especially the Fort Loudon Dam tailwater, where flood elevations were on the order of 19 feet higher than mean summer operating levels. Greater daily fluctuations in elevation at the Fort Loudon tailwater are the result of electrical power generation at that project. It should be expected that these minor fluctuations in tailwater elevation decrease in a downstream direction, and that time-averages of elevations recorded by the tailwater gage are more reflective of conditions at the Tellico tailwater, one mile downstream.

A review of the plotted piezometric data in Figures 12-22 reveals important trends as well as suspect and invalid observations. Most of the isolated extreme maximum/minimum values that are not explained by headwater/tailwater variations are hypothesized to be erroneous. This hypothesis will be further investigated in subsequent sections.

Most piezometers located upstream of the grout curtain fluctuate closely with headwater. Piezometers upstream of the grout curtain at location U-1 fluctuate with headwater in the elevation 790-813 range, with the exception of piezometer BU-1, which fluctuates with headwater in the elevation 758-763 range (see Figure 12). Piezometers upstream of the grout curtain at location U-2 fluctuate with headwater in the elevation 795-814 range, with the exception of piezometer BU-2, which fluctuates with headwater in the elevation 780-790 range (see Figure 13). Piezometers upstream of the grout curtain in the basal sand and gravel layer at location U-3 fluctuate closely with headwater in the elevation 802-815 range (see Figure 14). An observation for piezometer CU-3 on February 17, 1982, of 821.3 ft is thought to be invalid. This

individual observation should be evaluated along with the reported maximum for piezometer CE of 805.9 ft. On this date, the reading recorded for piezometers CU-1 and CE exceeded the mean values (Table 3) by 11.5 and 12.1 ft respectively. Since these piezometers are measured consecutively, a temporary malfunction of the bourdon-type input line gage seems likely.

Piezometers located in the cutoff trench fill (designation E, see Figure 15), vary with headwater generally in elevation range 790-799 ft. For the period observed, a slight increasing trend is noted. This trend is thought to be characteristic of the effects of pore fluid compression in the cutoff trench fill.

Piezometers located downstream of the cutoff trench (designations D-1 through D-6, see Figures 16-21) vary with tailwater in the general elevation range of 734-750 ft, with the following noted exceptions. Piezometers ED-2 and ED-3 vary more closely with headwater in the elevation 781-794 range. Piezometer ED-6 only recorded one reading above 0 psi. This piezometer is located in a right abutment terrace gravel approximately 40 ft above other D-6 piezometers, and is probably above the mean phreatic surface. As discussed, the mechanics of the Gloetzl pressure devices prevent the measurement of negative pore pressure. In this case, bypass would occur at 0 psig and give no information on the magnitude of negative pressure. Negative pore pressures are therefore possible at the location of piezometer ED-6.

An erratic, decreasing trend is shown for piezometer DD-5 (Figure 20). Until early 1984, this piezometer fluctuated closely in magnitude with other designation D-5 piezometers. On January 25, 1985, the

instrument recorded a minimum of 707.8 ft, approximately 25 ft lower than heads recorded on that date by other DD-5 piezometers. Particulates introduced between the by-pass valve and diaphragm are a possible source of this behavior.

Standpipe piezometers along the downstream toe of the embankment (Range H) vary closely with tailwater elevations, as shown in Figure 22. This figure shows only the maximum and minimum heads recorded by Range H piezometers, since most of these piezometers fluctuate closely together. The mean heads for these piezometers (Table 3) are 0-2 ft above the mean 3-day tailwater average (TWAVG3) of 739.76 ft. Standpipe piezometers H-21, H-22, and H-25 vary with tailwater at mean elevations of 742.12 ft, 746.10 ft and 747.99 ft consecutively, while piezometers H-22 and H-23 were normally dry.

The preceding data assessment, made from the plots and statistics presented, generally corroborates a data assessment of the instrumentation made by TVA engineers (47,48). In an internal memorandum assessing special data observations in the May 1984 flood (50), TVA engineers noted that observations at the Tellico project were most affected, attributing this to the record headwater and tailwater elevations at the project. However, the conclusion stated in this memorandum was that, in general, the levels recorded "did not indicate any structural distress or unsafe conditions" (50).

#### IV.3 Correlation Analysis

In the following section, correlation statistics are presented for the subject data. Of primary interest is the correlation of the

piezometric data to the various time-averages of headwater/tailwater (HW/TW) variables presented in the preceding section.

The statistics presented are sample correlation coefficients ( $r$ ) for piezometer reading elevations vs HW/TW variables. According to Younger, correlation coefficients measure the direction and strength of relationships between variables (62:243). More specifically, these statistics measure the strength of linear association between variables. A formula for the sample correlation coefficient ( $r$ ) is provided in Section A.1 in the Appendix. Three values of  $r$  may be objectively interpreted with respect to a problem. Correlation coefficients of  $r = 1$  and  $r = -1$  indicate perfect (direct or indirect) linear relationships between two variables, while the condition  $r = 0$  indicates no relationship between the variables. Other values of  $r$  have no physical meaning, and may only be subjectively interpreted in terms of the problem. As will be discussed in subsequent sections, correlation statistics are also important to the understanding of the multiple regression problem.

A series of correlation matrices are given in Tables 5-9. Tables 5 and 6 show correlation coefficients for the piezometers vs the headwater and tailwater variables respectively. Tables 7-9 show multicorrelation among the respective HW/TW variables.

In general, results of the correlation analysis show strong correlation between the observed piezometric elevations and the various HW/TW variables. Younger (62:24(4)) presents the following relative scale for the interpretation of absolute correlation coefficients:

TABLE 5. CORRELATION COEFFICIENTS FOR PIEZOMETERS VS HEADWATER VARIABLES

| PIEZOMETER | HW    | HWAVG3 | HWAVG5 | HWAVG10 | HWAVG30 | HW4T06 | HW7T09 | HW10T012 |
|------------|-------|--------|--------|---------|---------|--------|--------|----------|
| AU-1       | .7692 | .7753  | .7721  | .7722   | .7616   | .7596  | .7637  | .7858    |
| AU-2       | .8574 | .8581  | .8562  | .8509   | .8014   | .8458  | .8373  | .8322    |
| AU-3       | .9380 | .9356  | .9295  | .9282   | .8989   | .9133  | .9184  | .9228    |
| AE         | .6417 | .6434  | .6379  | .6355   | .6879   | .6209  | .6285  | .6395    |
| AD-1       | .7636 | .7751  | .7648  | .7531   | .7012   | .7341  | .7434  | .7218    |
| AD-2       | .6006 | .6212  | .6191  | .6047   | .5496   | .5980  | .5914  | .5795    |
| AD-3       | .3677 | .3861  | .3805  | .3680   | .3286   | .3571  | .3593  | .3579    |
| AD-4       | .7450 | .7572  | .7490  | .7364   | .6948   | .7227  | .7237  | .6982    |
| AD-5       | .7591 | .7725  | .7650  | .7519   | .7118   | .7371  | .7412  | .7143    |
| AD-6       | .7600 | .7747  | .7654  | .7525   | .7103   | .7348  | .7406  | .7185    |
| BU-1       | .7470 | .7509  | .7447  | .7325   | .7057   | .7211  | .7146  | .7203    |
| BU-2       | .0697 | .0932  | .1037  | .1126   | .1637   | .1186  | .1181  | .1338    |
| BU-3       | .8588 | .8548  | .8528  | .8490   | .8090   | .8405  | .8384  | .8328    |
| BE         | .7960 | .7985  | .7974  | .8053   | .7979   | .7932  | .8052  | .8084    |
| BD-1       | .7752 | .7914  | .7849  | .7769   | .7393   | .7604  | .7678  | .7608    |
| BD-2       | .5890 | .5951  | .5972  | .5972   | .5434   | .5909  | .5965  | .5914    |
| BD-3       | .7896 | .8065  | .7999  | .7966   | .7594   | .7775  | .7942  | .7725    |
| BD-4       | .6039 | .6224  | .6152  | .6074   | .5682   | .5919  | .6003  | .5818    |
| BD-5       | .7728 | .7821  | .7749  | .7626   | .7116   | .7482  | .7515  | .7288    |
| BD-6       | .7858 | .8089  | .8051  | .7959   | .7657   | .7825  | .7865  | .7703    |
| CU-1       | .8527 | .8440  | .8320  | .8292   | .7901   | .8078  | .8220  | .8111    |
| CU-2       | .8356 | .8303  | .8300  | .8287   | .7867   | .8215  | .8192  | .8157    |
| CU-3       | .6710 | .6664  | .6660  | .6709   | .6528   | .6623  | .6698  | .6763    |
| CE         | .3012 | .2979  | .2993  | .3104   | .3281   | .3043  | .3183  | .3258    |
| CD-1       | .7644 | .7686  | .7666  | .7689   | .7291   | .7582  | .7653  | .7617    |
| CD-2       | .6534 | .6684  | .6622  | .6405   | .5541   | .6345  | .6216  | .5866    |
| CD-3       | .6995 | .7113  | .7027  | .6832   | .6130   | .6706  | .6662  | .6358    |
| CD-4       | .7162 | .7355  | .7260  | .7090   | .6553   | .6948  | .6940  | .6701    |
| CD-5       | .7571 | .7709  | .7678  | .7526   | .7021   | .7496  | .7379  | .7035    |
| CD-6       | .7396 | .7555  | .7471  | .7320   | .6754   | .7183  | .7192  | .6886    |
| DU-1       | .8526 | .8474  | .8462  | .8409   | .8008   | .8355  | .8302  | .8180    |
| DU-2       | .7173 | .7166  | .7074  | .6964   | .6327   | .6833  | .6825  | .6733    |
| DD-1       | .7299 | .7508  | .7423  | .7237   | .6701   | .7098  | .7058  | .6906    |
| DD-2       | .7100 | .7300  | .7213  | .7026   | .6376   | .6884  | .6861  | .6601    |
| DD-4       | .7104 | .7251  | .7179  | .7031   | .6533   | .6894  | .6894  | .6722    |
| DD-5       | .3274 | .3523  | .3571  | .3593   | .3266   | .3508  | .3659  | .3723    |

TABLE 5 (CONTINUED)

| PIEZOMETER | HW    | HWAVG3 | HWAVG5 | HWAVG10 | HWAVG30 | HW4T06 | HW7T09 | HW10T012 |
|------------|-------|--------|--------|---------|---------|--------|--------|----------|
| EU-1       | .4629 | .4532  | .4428  | .4477   | .4251   | .4285  | .4448  | .4528    |
| EU-2       | .9194 | .9294  | .9234  | .9185   | .8949   | .9063  | .9041  | .9100    |
| EU-3       | .9599 | .9583  | .9537  | .9512   | .9039   | .9419  | .9416  | .9265    |
| EE         | .8371 | .8468  | .8390  | .8325   | .8280   | .8194  | .8178  | .8266    |
| ED-1       | .7019 | .7154  | .7069  | .6960   | .6334   | .6807  | .6863  | .6578    |
| ED-2       | .7789 | .7741  | .7630  | .7496   | .7033   | .7382  | .7303  | .7157    |
| ED-3       | .6806 | .6820  | .6714  | .6733   | .6633   | .6556  | .6693  | .6701    |
| ED-4       | .4140 | .4350  | .4380  | .4253   | .3835   | .4339  | .4091  | .4046    |
| ED-5       | .4700 | .4817  | .4787  | .4755   | .4209   | .4689  | .4758  | .4385    |
| ED-6       | .0757 | .0764  | .0856  | .0844   | .0929   | .0951  | .0807  | .0938    |
| H-1        | .7289 | .7412  | .7325  | .7177   | .6635   | .7030  | .7058  | .6750    |
| H-2        | .7459 | .7601  | .7527  | .7401   | .6928   | .7254  | .7296  | .7012    |
| H-3        | .7863 | .7921  | .7869  | .7851   | .7482   | .7697  | .7824  | .7617    |
| H-4        | .7666 | .7790  | .7715  | .7677   | .7384   | .7497  | .7641  | .7411    |
| H-5        | .7621 | .7757  | .7714  | .7714   | .7363   | .7555  | .7712  | .7454    |
| H-6        | .6780 | .6962  | .6916  | .6848   | .6440   | .6735  | .6793  | .6571    |
| H-7        | .7284 | .7423  | .7379  | .7347   | .7043   | .7206  | .7320  | .7084    |
| H-8        | .7040 | .7194  | .7110  | .6952   | .6273   | .6810  | .6836  | .6473    |
| H-8A       | .7064 | .7229  | .7154  | .7009   | .6349   | .6872  | .6908  | .6536    |
| H-9        | .6852 | .6998  | .6894  | .6733   | .6046   | .6569  | .6619  | .6273    |
| H-10       | .6924 | .7054  | .6957  | .6804   | .6133   | .6643  | .6701  | .6338    |
| H-11       | .6988 | .7156  | .7078  | .6899   | .6214   | .6780  | .6762  | .6397    |
| H-12       | .6949 | .7108  | .7030  | .6866   | .6207   | .6740  | .6747  | .6375    |
| H-13       | .6728 | .6903  | .6814  | .6647   | .5950   | .6499  | .6525  | .6185    |
| H-14       | .6497 | .6644  | .6556  | .6397   | .5730   | .6255  | .6283  | .5952    |
| H-15       | .6885 | .7074  | .6999  | .6827   | .6177   | .6705  | .6701  | .6344    |
| H-16       | .6842 | .7067  | .7002  | .6855   | .6184   | .6728  | .6758  | .6403    |
| H-17       | .6872 | .7033  | .6952  | .6782   | .6079   | .6645  | .6662  | .6281    |
| H-18       | .6507 | .6635  | .6542  | .6372   | .5653   | .6220  | .6255  | .5863    |
| H-19       | .6794 | .6978  | .6895  | .6734   | .6080   | .6620  | .6598  | .6240    |
| H-20       | .6718 | .6883  | .6796  | .6634   | .5974   | .6488  | .6522  | .6156    |
| H-21       | .6645 | .6812  | .6732  | .6587   | .5918   | .6456  | .6487  | .6111    |
| H-22       | .5496 | .5587  | .5524  | .5500   | .4941   | .5351  | .5512  | .5173    |
| H-23       | .2280 | .3348  | .3312  | .2615   | .0770   | .2770  | .2100  | .0848    |
| H-24       | .1931 | .2025  | .1629  | .0721   | .0280   | .0748  | -.0495 | .0563    |
| H-25       | .6839 | .6994  | .6838  | .6530   | .5678   | .6329  | .6274  | .5843    |

TABLE 6. CORRELATION COEFFICIENTS FOR PIEZOMETERS VS TAILWATER VARIABLES

| PIEZOMETER | TWAVG3 | TWAVG5 | TWAVG10 | TWAVG30 | TW4TO6 | TW7TO9 | TW10TO12 |
|------------|--------|--------|---------|---------|--------|--------|----------|
| AU-1       | .4625  | .4585  | .4721   | .5312   | .4481  | .4213  | .5139    |
| AU-2       | .6530  | .6481  | .6642   | .6521   | .6303  | .5992  | .6140    |
| AU-3       | .5556  | .5575  | .5827   | .6274   | .5528  | .5388  | .5856    |
| AE         | .4943  | .5063  | .5345   | .6350   | .5170  | .5143  | .5341    |
| AD-1       | .8710  | .8670  | .8583   | .8154   | .8264  | .7435  | .7163    |
| AD-2       | .7839  | .7791  | .7874   | .7362   | .7510  | .7209  | .6328    |
| AD-3       | .5240  | .5298  | .5714   | .5643   | .5568  | .5646  | .4797    |
| AD-4       | .8407  | .8360  | .7954   | .7014   | .7747  | .6485  | .6247    |
| AD-5       | .9074  | .9113  | .8765   | .7757   | .8697  | .7278  | .6691    |
| AD-6       | .9070  | .9090  | .8987   | .8245   | .8783  | .7768  | .7089    |
| BU-1       | .6693  | .6742  | .6692   | .6271   | .6568  | .5829  | .5436    |
| BU-2       | -.1419 | -.1539 | -.1918  | -.1420  | -.1933 | -.2276 | -.1263   |
| BU-3       | .5407  | .5376  | .5541   | .6039   | .5183  | .5007  | .5493    |
| BE         | .5081  | .5089  | .5537   | .6348   | .5085  | .5444  | .5666    |
| BD-1       | .8439  | .8471  | .8528   | .8153   | .8267  | .7574  | .7500    |
| BD-2       | .6971  | .7014  | .6997   | .6231   | .6896  | .6010  | .5755    |
| BD-3       | .8973  | .9057  | .9191   | .8849   | .8965  | .8313  | .7775    |
| BD-4       | .6985  | .7008  | .7232   | .7189   | .6905  | .6718  | .6576    |
| BD-5       | .9324  | .9340  | .9277   | .8201   | .9005  | .8130  | .7377    |
| BD-6       | .8546  | .8537  | .8560   | .8358   | .8233  | .7676  | .7080    |
| CU-1       | .5829  | .5906  | .6193   | .6429   | .5952  | .5749  | .5843    |
| CU-2       | .6068  | .5966  | .6193   | .6468   | .5713  | .5796  | .5672    |
| CU-3       | .5952  | .6106  | .6632   | .6624   | .6401  | .6466  | .6833    |
| CE         | .3920  | .4146  | .4820   | .4987   | .4785  | .5069  | .5303    |
| CD-1       | .6929  | .6968  | .7856   | .8481   | .7382  | .8085  | .8257    |
| CD-2       | .8370  | .8311  | .7943   | .6581   | .7891  | .6533  | .5251    |
| CD-3       | .9505  | .9485  | .9231   | .7722   | .9003  | .7933  | .6606    |
| CD-4       | .9151  | .9140  | .8898   | .8082   | .8731  | .7573  | .6937    |
| CD-5       | .8892  | .8906  | .8656   | .7664   | .8567  | .7273  | .6932    |
| CD-6       | .9476  | .9521  | .9531   | .8693   | .9314  | .8471  | .7645    |
| DU-1       | .5060  | .5070  | .5179   | .5525   | .5016  | .4582  | .5226    |
| DU-2       | .4667  | .4603  | .4327   | .4553   | .4210  | .3394  | .4085    |
| DD-1       | .8940  | .8894  | .8543   | .7669   | .8381  | .7072  | .6772    |
| DD-2       | .9418  | .9395  | .9072   | .7909   | .8901  | .7647  | .6849    |
| DD-4       | .8611  | .8625  | .8383   | .7574   | .8233  | .7086  | .6601    |
| DD-5       | .3822  | .3590  | .3823   | .3627   | .3377  | .3666  | .3656    |

TABLE 6 (CONTINUED)

| PIEZOMETER | TWAVG3 | TWAVG5 | TWAVG10 | TWAVG30 | TW4T06 | TW7T09 | TW10T012 |
|------------|--------|--------|---------|---------|--------|--------|----------|
| EU-1       | .2611  | .2894  | .3100   | .3334   | .3239  | .2927  | .2573    |
| EU-2       | .5449  | .5476  | .5726   | .6241   | .5418  | .5402  | .5366    |
| EU-3       | .5833  | .5890  | .6129   | .6446   | .5851  | .5660  | .5731    |
| EE         | .5257  | .5252  | .5277   | .5934   | .5019  | .4606  | .5390    |
| ED-1       | .8869  | .8959  | .9014   | .8389   | .8844  | .8069  | .7388    |
| ED-2       | .4984  | .5057  | .5321   | .5648   | .4993  | .5153  | .4841    |
| ED-3       | .4752  | .4878  | .5081   | .5679   | .4983  | .4683  | .4959    |
| ED-4       | .5895  | .5756  | .5403   | .4858   | .5365  | .4085  | .4528    |
| ED-5       | .6586  | .6720  | .6654   | .5810   | .6727  | .5765  | .4394    |
| ED-6       | .1048  | .0665  | .0529   | .1110   | .0013  | .0495  | .0230    |
| H-1        | .9587  | .9644  | .9518   | .8407   | .9368  | .8254  | .7464    |
| H-2        | .9520  | .9600  | .9511   | .8534   | .9393  | .8272  | .7632    |
| H-3        | .8876  | .9028  | .9414   | .9207   | .9225  | .8769  | .8504    |
| H-4        | .8982  | .9158  | .9485   | .9183   | .9338  | .8784  | .8401    |
| H-5        | .8472  | .8667  | .9019   | .8976   | .8847  | .8473  | .8126    |
| H-6        | .8746  | .8827  | .8954   | .8174   | .8791  | .8099  | .7135    |
| H-7        | .9167  | .9318  | .9589   | .9141   | .9403  | .8882  | .8138    |
| H-8        | .9710  | .9747  | .9538   | .8213   | .9416  | .8173  | .7314    |
| H-8A       | .9712  | .9753  | .9564   | .8251   | .9438  | .8227  | .7356    |
| H-9        | .9606  | .9654  | .9451   | .8068   | .9360  | .8104  | .7156    |
| H-10       | .9671  | .9710  | .9498   | .8090   | .9402  | .8111  | .7262    |
| H-11       | .9740  | .9764  | .9483   | .8028   | .9373  | .8039  | .7177    |
| H-12       | .9713  | .9757  | .9507   | .8058   | .9413  | .8109  | .7158    |
| H-13       | .9662  | .9686  | .9425   | .7965   | .9308  | .8018  | .7083    |
| H-14       | .9657  | .9712  | .9538   | .8090   | .9444  | .8201  | .7389    |
| H-15       | .9731  | .9746  | .9475   | .8093   | .9364  | .8038  | .7232    |
| H-16       | .9607  | .9601  | .9390   | .8073   | .9238  | .8048  | .7270    |
| H-17       | .9699  | .9732  | .9486   | .8008   | .9362  | .8106  | .7117    |
| H-18       | .9444  | .9483  | .9247   | .7802   | .9094  | .7873  | .7117    |
| H-19       | .9524  | .9571  | .9343   | .8051   | .9288  | .7952  | .7153    |
| H-20       | .9595  | .9631  | .9385   | .8059   | .9263  | .8002  | .7093    |
| H-21       | .9590  | .9667  | .9479   | .8296   | .9421  | .8129  | .7337    |
| H-22       | .7489  | .7745  | .7926   | .7747   | .7950  | .7217  | .6853    |
| H-23       | .6778  | .6733  | .6509   | .2830   | .6633  | .5680  | -.3880   |
| H-24       | .6149  | .5879  | .4950   | .5702   | .4104  | .4879  | .0902    |
| H-25       | .8469  | .8540  | .8557   | .8075   | .8565  | .7545  | .6319    |

TABLE 7. CORRELATION COEFFICIENTS FOR HEADWATER VS TAILWATER VARIABLES

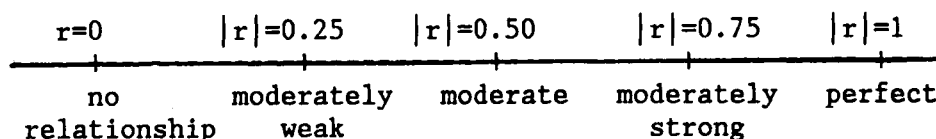
| VARIABLE | HW    | HWAVG3 | HWAVG5 | HWAVG10 | HWAVG30 | HW4TO6 | HW7TO9 | HW10TO12 |
|----------|-------|--------|--------|---------|---------|--------|--------|----------|
| TWAVG3   | .6299 | .6537  | .6495  | .6293   | .5557   | .6236  | .6148  | .5721    |
| TWAVG5   | .6341 | .6523  | .6466  | .6295   | .5609   | .6203  | .6182  | .5750    |
| TWAVG10  | .6583 | .6650  | .6578  | .6506   | .5944   | .6347  | .6470  | .6138    |
| TWAVG30  | .6736 | .6847  | .6815  | .6884   | .6943   | .6717  | .6938  | .6831    |
| TW4TO6   | .6283 | .6327  | .6239  | .6167   | .5625   | .6000  | .6143  | .5758    |
| TW7TO9   | .6072 | .6036  | .5963  | .6015   | .5696   | .5794  | .6073  | .5891    |
| TW10TO12 | .6215 | .6144  | .6114  | .6221   | .6083   | .6071  | .6281  | .6315    |

TABLE 8. CORRELATION COEFFICIENTS FOR HEADWATER VARIABLES

| VARIABLE | HW     | HWAVG3 | HWAVG5 | HWAVG10 | HWAVG30 | HW4TO6 | HW7TO9 | HW10TO12 |
|----------|--------|--------|--------|---------|---------|--------|--------|----------|
| HW       | 1.0000 | .9924  | .9878  | .9844   | .9344   | .9746  | .9738  | .9576    |
| HWAVG3   | .9924  | 1.0000 | .9982  | .9932   | .9467   | .9873  | .9811  | .9656    |
| HWAVG5   | .9878  | .9982  | 1.0000 | .9966   | .9526   | .9946  | .9858  | .9712    |
| HWAVG10  | .9844  | .9932  | .9966  | 1.0000  | .9643   | .9961  | .9960  | .9839    |
| HWAVG30  | .9344  | .9467  | .9526  | .9643   | 1.0000  | .9578  | .9668  | .9803    |
| HW4TO6   | .9746  | .9873  | .9946  | .9961   | .9578   | 1.0000 | .9889  | .9757    |
| HW7TO9   | .9738  | .9810  | .9858  | .9960   | .9668   | .9889  | 1.0000 | .9871    |
| HW10TO12 | .9576  | .9657  | .9712  | .9839   | .9803   | .9757  | .9871  | 1.0000   |

TABLE 9. CORRELATION COEFFICIENTS FOR TAILWATER VARIABLES

| VARIABLE | TWAVG3 | TWAVG5 | TWAVG10 | TWAVG30 | TW4TO6 | TW7TO9 | TW10TO12 |
|----------|--------|--------|---------|---------|--------|--------|----------|
| TWAVG3   | 1.0000 | .9937  | .9478   | .7673   | .9288  | .7880  | .6760    |
| TWAVG5   | .9937  | 1.0000 | .9656   | .7843   | .9595  | .8151  | .7005    |
| TWAVG10  | .9478  | .9656  | 1.0000  | .8766   | .9824  | .9335  | .8271    |
| TWAVG30  | .7673  | .7843  | .8766   | 1.0000  | .8411  | .9007  | .8824    |
| TW4TO6   | .9288  | .9595  | .9824   | .8411   | 1.0000 | .8921  | .7842    |
| TW7TO9   | .7880  | .8151  | .9335   | .9007   | .8921  | 1.0000 | .8710    |
| TW10TO12 | .6760  | .7005  | .8271   | .8824   | .7842  | .8710  | 1.0000   |



Using this scale, the direction of the relationship (inverse or direct) would be determined by the sign on  $r$ . According to this subjective interpretation, an overall assessment of the correlation results presented would be "moderately strong."

For a given piezometer, correlation differs among the respective HW/TW time-averages, indicating that time is a factor in the piezometric response to headwater/tailwater fluctuations.

In general, piezometers located upstream of the cutoff trench CL (designation U) and those located in the cutoff trench fill (designation E) correlate more strongly with headwater variables, while those located downstream of this CL (designation D and range H) correlated strongly with tailwater variables. This condition is consistent with the location of the instrumentation within the respective sections.

From the correlation analysis of piezometric data vs HW/TW variables, an interpretation of flow conditions as monitored by the data can be made by (1) assessing the magnitude of correlation, (2) assessing time effects by comparing correlation of the various headwater/tailwater time-averages, and (3) drawing an inference regarding the significance of the results.

For the case of piezometers correlating strongly with instantaneous headwater or 3-day antecedent averages, it may be inferred that the instrument is located in a highly permeable strata or in a rock joint,

where fluctuations in headwater or tailwater would be effectively transmitted. Standpipe piezometers H-1 through H-21, which generally show maximum correlation with tailwater variables in excess of 0.9, indicate the permeable nature of the alluvial sand and gravel layer and shallow bedrock fracture system.

Piezometers exhibiting low correlation with headwater/tailwater conditions can indicate instrument malfunction or placement in a zone of low permeability or connectivity. For the case of piezometer ED-6, low correlation (on the order of 0.1) reflects the inability of the instrument to function. However, low correlation between piezometer BU-2 and headwater does not prove grounds for rejection of data. Here, lack of correlation can apparently be attributed to placement of the instrument in a zone of less weathered, "tight" bedrock.

The results of the correlation analysis provide a basis for further investigation of the relationship between the headwater/tailwater variables and the observed piezometric elevations. This will be accomplished using regression.

#### IV.4 Regression Analysis

The purpose of this section is to model the piezometric data. The procedure used will be to select deterministic equations based on observed and/or hypothesized flow conditions and to fit equivalent probabilistic models to the data using regression. The regression analysis will include a statement of hypothesized flow conditions and resultant regression models, some discussion on the applicability of the

derived models to the Tellico data, and a presentation of results. The performance and implications of the modeling results will be discussed in Section 5.

#### IV.4.1 Regression Model Formulation

In a regression analysis, model choice is influenced by the type of data collected, existing physical relationships, and available resources. In many cases, the model selected for a particular purpose is a simplification of actual conditions. For considerations of economy, simplified solutions are sought to engineering problems if they can be justified on the basis of performance. In this analysis, as with many other seepage analyses, this approach results in the selection of steady flow equations and the assumption that Darcy's Law applies. However, because variations in the behavior of the seepage field, as recorded by the piezometers, show the possible effects of heterogeneity, transient flow conditions, and infiltration, model error is to be expected in some cases. As will be shown, use of steady flow equations results in linear models--this is a significant advantage in terms of computational ease.

##### IV.4.1.1 Steady Flow Model

For this model, it is assumed that steady flow through a Darcian Continuum applies to the problem at hand. Figure 23 shows this condition for a simplified section. Headwater and tailwater elevations as well as flow through the section are constant. For this condition, the Bernoulli equation, modified for negligible velocity head differential

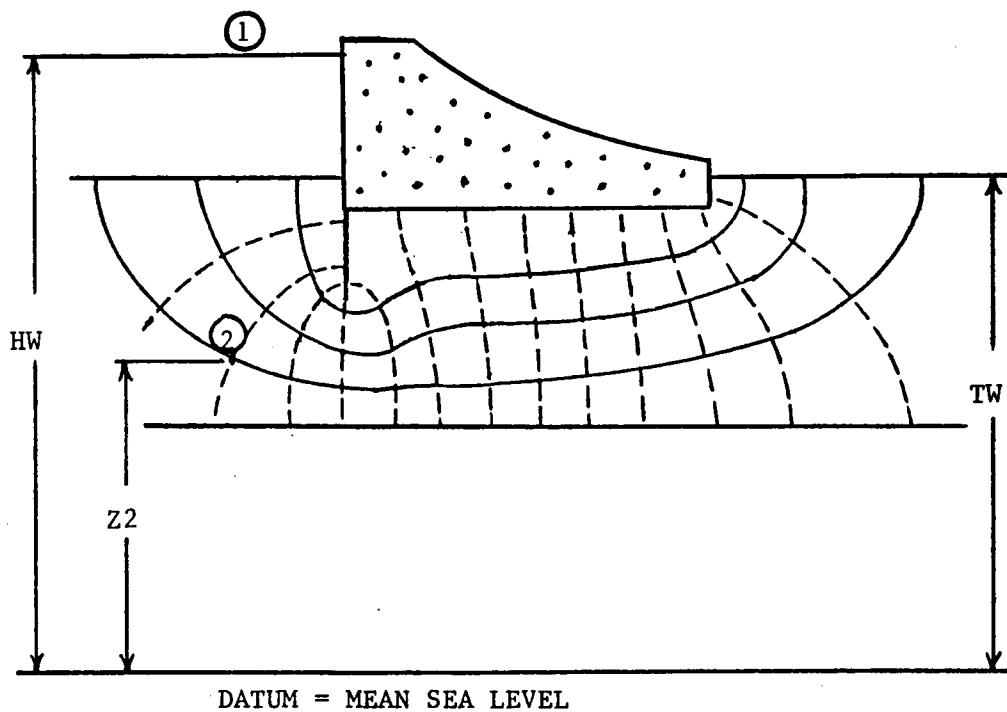


FIGURE 23. STEADY FLOW MODEL FOR SEEPAGE THROUGH A HOMOGENEOUS ISOTROPIC FOUNDATION

and viscous resistance within porous media applies. Substituting the conditions shown in Figure 23 into Equ. 5 yields the following:

$$HW = Z2 + H_p + h_l , \quad (20)$$

where

$Z2$  = instrument elevation,

$H_p$  = pressure head at point 2 ( $P/\gamma$ ),

$h_l$  = head dissipated by viscous resistance of porous media between points 1 and 2, and

$HW$  = steady-state headwater elevation.

Equ. 13 gives the head loss between any two adjacent equipotential drops to be:

$$h_l = \frac{H}{N_t} . \quad (21)$$

The head loss between points 1 and 2 can thus be calculated by multiplying by the number of equipotential drops between the 2 points  $N_d$ :

$$h_{l_{1-2}} = H \frac{(N_d)}{(N_t)} . \quad (21)$$

By substitution of headwater and tailwater elevations for  $H$  and defining the constant fractional value  $(N_d/N_t)$  as  $K_e$ , the following expression for  $h_l$  results:

$$h_l = K_e(HW - TW) . \quad (23)$$

Substitution of Equ. 22 into Equ. 20 yields the following relationship:

$$HW = Z2 + H_p + K_e(HW - TW) . \quad (24)$$

Equ. 24 is further simplified by recognizing the quantity  $(Z2 + H_p)$  to be the hydraulic head at point 2, as defined in Equ. 7. An expression for the hydraulic head at point 2 (or any other point in the porous media) can thus be written as:

$$h = HW - K_e(HW - TW) = (1 - K_e)(HW) + (K_e)(TW) . \quad (25)$$

Equ. 25 states that the total energy at a point in a porous media is the total energy available in the system minus the energy dissipated by viscous flow at that point along a pathline through the media. The assumptions for this equation are steady flow ( $q = \text{const.}$ ), negligible velocity head differential, and viscous flow through porous media (laminar flow, Darcy's Law applies).

For the assumed conditions, the quantity  $K_e$  is a constant multiplier, independent of the steady-state reservoir operating head  $H$ .  $K_e$  is thus a normalized fraction representing the energy dissipated along a pathline upstream from a given point divided by the total energy dissipated through the media in the system.

Equ. 25 forms the basis for a multiple linear regression model to be applied to the Tellico data. The following probabilistic model is a regression fit to Equ. 25:

$$Y = b_1(X_1) + b_2(X_2) + e , \quad (26)$$

where

$Y$  = dependent variable ( $h$ ),

$X_1, X_2$  = independent variables ( $HW, TW$ ),

$b_1, b_2$  = regression coefficients, and

$e$  = error.

Several points regarding the suitability of and interpretation of Equ. 26 should be made. First, application of the equation to data representing varying headwater/tailwater conditions and piezometric heads is a seeming contradiction to the assumption of steady flow inherent in the derivation of Equ. 25. For Equ. 26, the effects of transient flow as well as other deviations from assumed conditions will be present in the error term as model error. The extent of this error will be dependent on whether unsteady flow is rapidly varied--this is not assumed to be the case for this problem. According to Younger, the error term ( $e$ ) in Equ. 26 is composed of model error arising from lack of fit (caused by imprecise model specification) and random error (50:18).

Equ. 26 is a zero-intercept statistical model, which differs from a standard linear regression problem (in which an intercept term is included) in several respects. A multiple regression model with an intercept parameter ( $a$ ) included may be stated as:

$$Y = a + b_1(X_1) + b_2(X_2) + e . \quad (27)$$

In Equ. 27,  $e$  varies for each observation and is not an estimable parameter--it is thus separable from the intercept term ( $a$ ).

Snedecor and Cochran caution about the use of the zero intercept model primarily because if model error is present, a fit through the origin is not necessarily the best fit (60:166). Equ. 27 presupposes that the best fit of the relationship passes through the origin (i.e., at  $X_1 = X_2 = 0$ ,  $Y = 0$ ). Instead, with the use of Equ. 27, the hypothesis that  $a = 0$  may possibly be tested. However, the intercept ( $a$ ) has no physical significance, because the model has no interpretation at values of  $X_1 = HW = 0$  and  $X_2 = TW = 0$ .

A second problem arises from the fact that the constants HW and TW (as defined in Figure 23) are, in reality, variables. A major problem is selecting which values of HW and TW should be used for the regression analysis. For this research, selection of variables for use in regression is made on the basis of the preceding correlation statistics. Specifically, the headwater and tailwater variables having the highest positive correlation with a given piezometer are selected for the regression. This procedure provides relative ease in computational logic and helps minimize use of computer resources. However, because of multicorrelation (subsequently discussed), this procedure does not always produce the model with the best fit.

Multicorrelation between predictor variables presents several possible problems with respect to application of Equ's. 26-27 to the Tellico data. According to Younger, the use of redundant predictor variables can cause large standard errors of the regression coefficients, resulting in an untrustworthy regression equation (62:355). Also, as discussed by Younger, the presence of multicollinearity causes

the regression coefficients to be "unreliable measures of the effects of their associated predictor variables" (62:317). Correlation coefficients on the magnitude of 0.6 in Table 7 (p. 89) show that multicorrelation between HW/TW variables is, indeed, present for this problem. Equating the regression coefficients  $b_1$  and  $b_2$  in Equ. 26 with the coefficients in Equ. 25 yields:

$$b_1 = (1 - K_e) \quad \text{and} \quad b_2 = K_e .$$

However, multicorrelation between predictors invalidates this ideal relationship. Multicorrelation thus complicates the interpretation of selected statistics and the model selection process itself.

#### IV.4.1.2 Hydrostatic Model

A hydrostatic model utilizes only one predictor variable, and is based on the assumption of effective seepage cutoff by the grout curtain. This model can be derived for the condition of constant headwater and tailwater elevations and by extension of the grout curtain shown in Figure 20 (p. 81) to the impervious boundary. For the condition of total seepage cutoff, the hydraulic head at any point is given as:

$$(a) \quad h = HW \quad \text{or} \quad (b) \quad h = TW . \quad (28)$$

Equation 28a would apply upstream of the grout curtain while Equation 28b would apply downstream of the structure. A regression model for this condition is:

$$Y = b(X) + e , \quad (29)$$

where

$Y$  = dependent variable (h),

$X$  = independent variable (HW or TW),

$b$  = regression coefficient, and

$e$  = error.

For the same reasons as with the previous model, Equ. 29 is modified to include an intercept term:

$$Y = a + b(X) + e . \quad (30)$$

This simple linear regression equation, using one headwater/tailwater predictor variable, avoids the problem of multicorrelation. For Equ's. 29-30, the best model fit for a given selection of predictor variables is achieved by choosing the variable having the highest correlation coefficient with the dependent variable. This logic is therefore applied in the selection of headwater/tailwater variables for the modeling process.

#### IV.4.2 Regression Model Application and Results

Equations 27 and 30 are two candidates selected for application to the Tellico data. It is acknowledged, however, that they are both based on idealized conditions. For example, neither model includes the effects of consolidation, and therefore would not strictly apply to the piezometers located in the embankment cutoff trench. For ease in

computational logic, however, the models are applied to all the piezometers. For each given piezometer, the models obtained from Equ's. 27 and 30 provide a basis for comparison and testing of hypothesized flow conditions.

The models stated in Equ's. 27 and 30 form conceptual frameworks for the analysis that must be modified somewhat for regression. Techniques of regression can only estimate the underlying relationships stated. According to Younger (62:19), the models stated in Equ's. 27 and 30 can be interpreted as saying that there is an imperfect relationship between the dependent and independent variables and furthermore, the exact values of  $a$ ,  $b$ ,  $b_1$ , and  $b_2$  can never be known. In recognition of this fact, it is appropriate to denote the numerical estimates of these parameters by a separate symbol. In subsequent references, the capitalized equivalents of these symbols ( $A$ ,  $B$ ,  $B_1$ , and  $B_2$ ) are used to denote that these are only estimates of model parameters. The regression equations corresponding to the models stated in Equ's. 27 and 30 thus become:

$$Y_h = A + B_1(X_1) + B_2(X_2) , \quad (31)$$

and

$$Y_h = A + B(X) , \quad (32)$$

where

$Y_h$  = predicted  $Y$  value,

$A$  = regression constant estimate, and

$B$ ,  $B_1$ ,  $B_2$  = regression coefficient estimates.

The derivation of calculating formulae for parameter estimates are based on the use of calculus. A brief discussion of this procedure is provided in the Appendix, Section A.2.

Equ. 31 has geometric interpretation as a plane through a 3-dimensional space of axes  $Y$ ,  $X_1$  and  $X_2$ , intersecting the  $Y$  axis at  $Y = A$ . Equ. 32 has geometrical interpretation as a straight line in 2-dimensional space of axes  $Y$  and  $X$ , intersecting the  $Y$  axis at  $Y = A$ .

Two important statistics commonly used in describing overall model performance in regression analysis are the coefficient of determination and the standard error of estimate. The sample coefficient of determination (R-SQUARE) is an estimate of the proportion of variation in the dependent variable  $Y$  which is explained by the model predictor variables. The standard error of estimate ( $S$ ) measures the average amount that observed  $Y$  values differ from predicted  $Y$  values. According to Younger (62:185), the assumption necessary for valid use of  $S$  is that the scatter of error around the regression equation is the same for every  $X$  value (homoscedasticity). Calculating formulae and a brief discussion of these statistics are presented in the Appendix, Sections A.3-A.4.

#### IV.4.2.1 Regression Model Results

Results of the regression analysis are presented in Tables 10-12. The statistics presented are limited to regression parameter estimates, the model standard error of estimate ( $S$ ) and the coefficient of determination (R-SQUARE). Tables 10 and 11 give multiple and simple linear

TABLE 10. MULTIPLE LINEAR REGRESSION MODEL STATEMENTS FOR PIEZOMETERS

| PIEZOMETER<br>HEAD<br>Y (ft) | REGRESSION<br>CONSTANT<br>A | REGRESSION<br>COEFFICIENT<br>B1 | MODEL STATEMENT <sup>a</sup><br>HEADWATER<br>VARIABLE<br>X1 | REGRESSION<br>COEFFICIENT<br>B2 | TAILWATER<br>VARIABLE<br>X2 | MODEL STD.<br>ERROR OF<br>ESTIMATE<br>S (ft) | MODEL STD.<br>ERROR OF<br>ESTIMATE<br>S (psi) | COEFF.<br>OF<br>DETERMIN.<br>R-SQUARE |
|------------------------------|-----------------------------|---------------------------------|-------------------------------------------------------------|---------------------------------|-----------------------------|----------------------------------------------|-----------------------------------------------|---------------------------------------|
| AU-1                         | = -142.46                   | + 1.1721                        | * HW1OTO12                                                  | + -0.0155                       | * TWAVG30                   | 2.01                                         | 0.87                                          | 61.8%                                 |
| AU-2                         | = -68.78                    | + 0.9084                        | * HWAvg3                                                    | + 0.1823                        | * TWAVG10                   | 1.39                                         | 0.60                                          | 75.2%                                 |
| AU-3                         | = -92.44                    | + 1.1219                        | * HW                                                        | + -0.0100                       | * TWAVG30                   | 0.94                                         | 0.41                                          | 88.0%                                 |
| AE                           | = 22.44                     | + 0.6117                        | * HWAvg30                                                   | + 0.3730                        | * TWAVG30                   | 1.87                                         | 0.81                                          | 52.1%                                 |
| AD-1                         | = 162.24                    | + 0.3383                        | * HWAvg3                                                    | + 0.4117                        | * TWAVG3                    | 0.88                                         | 0.38                                          | 83.3%                                 |
| AD-2                         | = 208.01                    | + 0.1591                        | * HWAvg3                                                    | + 0.5450                        | * TWAVG10                   | 1.26                                         | 0.54                                          | 63.7%                                 |
| AD-3                         | = 250.38                    | + 0.0141                        | * HWAvg3                                                    | + 0.6464                        | * TWAVG10                   | 2.41                                         | 1.05                                          | 32.7%                                 |
| AD-4                         | = 49.62                     | + 0.4163                        | * HWAvg3                                                    | + 0.4763                        | * TWAVG3                    | 1.23                                         | 0.53                                          | 78.2%                                 |
| AD-5                         | = 144.38                    | + 0.2898                        | * HWAvg3                                                    | + 0.4838                        | * TWAVG5                    | 0.72                                         | 0.31                                          | 88.6%                                 |
| AD-6                         | = 148.96                    | + 0.2983                        | * HWAvg3                                                    | + 0.4705                        | * TWAVG5                    | 0.70                                         | 0.30                                          | 88.8%                                 |
| BU-1                         | = 131.35                    | + 0.5545                        | * HWAvg3                                                    | + 0.2398                        | * TWAVG5                    | 1.44                                         | 0.62                                          | 62.3%                                 |
| BU-2                         | = 717.76                    | + 0.4306                        | * HWAvg30                                                   | + -0.3815                       | * TW1OTO12                  | 2.25                                         | 0.97                                          | 10.8%                                 |
| BU-3                         | = -15.05                    | + 0.9640                        | * HW                                                        | + 0.0559                        | * TWAVG30                   | 1.36                                         | 0.59                                          | 73.9%                                 |
| BE                           | = 193.36                    | + 0.6165                        | * HW1OTO12                                                  | + 0.1355                        | * TWAVG30                   | 1.11                                         | 0.48                                          | 66.6%                                 |
| BD-1                         | = 70.61                     | + 0.3798                        | * HWAvg3                                                    | + 0.4939                        | * TWAVG10                   | 0.93                                         | 0.40                                          | 81.7%                                 |
| BD-2                         | = 181.84                    | + 0.2943                        | * HWAvg10                                                   | + 0.4374                        | * TWAVG5                    | 1.74                                         | 0.76                                          | 53.2%                                 |
| BD-3                         | = 138.18                    | + 0.2849                        | * HWAvg3                                                    | + 0.4986                        | * TWAVG10                   | 0.55                                         | 0.24                                          | 91.3%                                 |
| BD-4                         | = 9.74                      | + 0.3237                        | * HWAvg3                                                    | + 0.6321                        | * TWAVG10                   | 1.94                                         | 0.84                                          | 55.9%                                 |
| BD-5                         | = 101.28                    | + 0.2994                        | * HWAvg3                                                    | + 0.5356                        | * TWAVG5                    | 0.63                                         | 0.27                                          | 92.4%                                 |
| BD-6                         | = 159.94                    | + 0.3434                        | * HWAvg3                                                    | + 0.4068                        | * TWAVG10                   | 0.74                                         | 0.32                                          | 83.6%                                 |
| CU-1                         | = -135.70                   | + 1.0066                        | * HW                                                        | + 0.1701                        | * TWAVG30                   | 1.54                                         | 0.67                                          | 73.6%                                 |
| CU-2                         | = -158.54                   | + 0.9934                        | * HW                                                        | + 0.2160                        | * TWAVG30                   | 1.67                                         | 0.72                                          | 71.1%                                 |
| CU-3                         | = -59.85                    | + 0.5528                        | * HW1OTO12                                                  | + 0.5689                        | * TW1OTO12                  | 1.97                                         | 0.85                                          | 56.7%                                 |
| CE                           | = 335.54                    | + 0.0108                        | * HWAvg30                                                   | + 0.6085                        | * TW1OTO12                  | 2.20                                         | 0.95                                          | 28.1%                                 |
| CD-1                         | = 7.39                      | + 0.3490                        | * HWAvg10                                                   | + 0.6088                        | * TWAVG30                   | 1.03                                         | 0.45                                          | 78.4%                                 |
| CD-2                         | = 43.54                     | + 0.2798                        | * HWAvg3                                                    | + 0.6349                        | * TWAVG3                    | 1.59                                         | 0.69                                          | 72.6%                                 |
| CD-3                         | = 173.26                    | + 0.1597                        | * HWAvg3                                                    | + 0.5922                        | * TWAVG3                    | 0.67                                         | 0.29                                          | 91.8%                                 |
| CD-4                         | = 73.49                     | + 0.2755                        | * HWAvg3                                                    | + 0.5988                        | * TWAVG3                    | 0.95                                         | 0.41                                          | 87.0%                                 |
| CD-5                         | = -7.54                     | + 0.3898                        | * HWAvg3                                                    | + 0.5807                        | * TWAVG5                    | 1.03                                         | 0.44                                          | 85.6%                                 |
| CD-6                         | = 1.03                      | + 0.2266                        | * HWAvg3                                                    | + 0.7494                        | * TWAVG10                   | 0.61                                         | 0.26                                          | 93.5%                                 |
| DU-1                         | = -92.68                    | + 1.1515                        | * HW                                                        | + -0.0543                       | * TWAVG30                   | 1.56                                         | 0.68                                          | 72.8%                                 |
| DU-2                         | = -56.81                    | + 1.0404                        | * HW                                                        | + 0.0251                        | * TWAVG3                    | 2.36                                         | 1.02                                          | 51.5%                                 |
| DD-1                         | = 56.47                     | + 0.3348                        | * HWAvg3                                                    | + 0.5575                        | * TWAVG3                    | 1.03                                         | 0.45                                          | 84.8%                                 |
| DD-2                         | = 92.75                     | + 0.2248                        | * HWAvg3                                                    | + 0.6273                        | * TWAVG3                    | 0.78                                         | 0.34                                          | 91.0%                                 |
| DD-4                         | = 37.59                     | + 0.3329                        | * HWAvg3                                                    | + 0.5819                        | * TWAVG5                    | 1.24                                         | 0.54                                          | 79.0%                                 |
| DD-5                         | = -283.22                   | + 0.6703                        | * HW1OTO12                                                  | + 0.6415                        | * TWAVG10                   | 6.06                                         | 2.62                                          | 17.7%                                 |

TABLE 10 (CONTINUED)

| -----MODEL STATEMENT <sup>a</sup> ----- |                             |                                 |                             |                                 |                             | MODEL STD.                     | MODEL STD.                      | COEFF.                      |
|-----------------------------------------|-----------------------------|---------------------------------|-----------------------------|---------------------------------|-----------------------------|--------------------------------|---------------------------------|-----------------------------|
| PIEZOMETER<br>HEAD<br>Y (ft)            | REGRESSION<br>CONSTANT<br>A | REGRESSION<br>COEFFICIENT<br>B1 | HEADWATER<br>VARIABLE<br>X1 | REGRESSION<br>COEFFICIENT<br>B2 | TAILWATER<br>VARIABLE<br>X2 | ERROR OF<br>ESTIMATE<br>S (ft) | ERROR OF<br>ESTIMATE<br>S (psi) | OF<br>DETERMIN.<br>R-SQUARE |
| EU-1                                    | = 73.81                     | + 0.8320                        | * HW                        | + 0.0780                        | * TWAVG30                   | 3.86                           | 1.67                            | 21.5%                       |
| EU-2                                    | = -6.28                     | + 1.0291                        | * HWAVG3                    | + -0.0263                       | * TWAVG30                   | 0.92                           | 0.40                            | 86.4%                       |
| EU-3                                    | = -39.55                    | + 1.0439                        | * HW                        | + 0.0038                        | * TWAVG30                   | 0.70                           | 0.30                            | 92.2%                       |
| EE                                      | = 320.81                    | + 0.5679                        | * HWAVG3                    | + 0.0182                        | * TWAVG30                   | 0.83                           | 0.36                            | 71.7%                       |
| ED-1                                    | = 48.06                     | + 0.2153                        | * HWAVG3                    | + 0.7052                        | * TWAVG10                   | 0.96                           | 0.42                            | 83.7%                       |
| ED-2                                    | = 194.38                    | + 0.6669                        | * HW                        | + 0.0694                        | * TWAVG30                   | 1.30                           | 0.56                            | 61.0%                       |
| ED-3                                    | = 274.41                    | + 0.4793                        | * HWAVG3                    | + 0.1716                        | * TWAVG30                   | 1.43                           | 0.62                            | 48.4%                       |
| ED-4                                    | = 360.33                    | + 0.1060                        | * HWAVG5                    | + 0.3983                        | * TWAVG3                    | 2.03                           | 0.88                            | 35.3%                       |
| ED-5                                    | = 63.53                     | + 0.1366                        | * HWAVG3                    | + 0.7675                        | * TW4TO6                    | 2.47                           | 1.07                            | 45.8%                       |
| ED-6                                    | = 761.66                    | + 0.0071                        | * HW4TO6                    | + 0.0165                        | * TWAVG30                   | 0.42                           | 0.18                            | 1.3%                        |
|                                         |                             |                                 |                             |                                 |                             |                                |                                 |                             |
| H-1                                     | = 183.38                    | + 0.1796                        | * HWAVG3                    | + 0.5573                        | * TWAVG5                    | 0.46                           | -                               | 95.2%                       |
| H-2                                     | = 195.55                    | + 0.2129                        | * HWAVG3                    | + 0.5047                        | * TWAVG5                    | 0.41                           | -                               | 95.7%                       |
| H-3                                     | = 193.33                    | + 0.2297                        | * HWAVG3                    | + 0.4891                        | * TWAVG10                   | 0.41                           | -                               | 94.1%                       |
| H-4                                     | = 203.04                    | + 0.2051                        | * HWAVG3                    | + 0.5030                        | * TWAVG10                   | 0.40                           | -                               | 94.4%                       |
| H-5                                     | = 171.48                    | + 0.2590                        | * HWAVG3                    | + 0.4862                        | * TWAVG10                   | 0.65                           | -                               | 87.4%                       |
| H-6                                     | = 188.49                    | + 0.1532                        | * HWAVG3                    | + 0.5792                        | * TWAVG10                   | 0.82                           | -                               | 82.0%                       |
| H-7                                     | = 261.48                    | + 0.1294                        | * HWAVG3                    | + 0.5068                        | * TWAVG10                   | 0.39                           | -                               | 94.0%                       |
| H-8                                     | = 137.87                    | + 0.1495                        | * HWAVG3                    | + 0.6514                        | * TWAVG5                    | 0.45                           | -                               | 96.3%                       |
| H-8A                                    | = 146.46                    | + 0.1522                        | * HWAVG3                    | + 0.6370                        | * TWAVG5                    | 0.43                           | -                               | 96.5%                       |
| H-9                                     | = 139.25                    | + 0.1287                        | * HWAVG3                    | + 0.6722                        | * TWAVG5                    | 0.59                           | -                               | 94.1%                       |
| H-10                                    | = 132.68                    | + 0.1326                        | * HWAVG3                    | + 0.6770                        | * TWAVG5                    | 0.53                           | -                               | 95.2%                       |
| H-11                                    | = 136.35                    | + 0.1418                        | * HWAVG3                    | + 0.6619                        | * TWAVG5                    | 0.45                           | -                               | 96.4%                       |
| H-12                                    | = 136.36                    | + 0.1349                        | * HWAVG3                    | + 0.6693                        | * TWAVG5                    | 0.47                           | -                               | 96.2%                       |
| H-13                                    | = 145.36                    | + 0.1079                        | * HWAVG3                    | + 0.6866                        | * TWAVG5                    | 0.57                           | -                               | 94.4%                       |
| H-14                                    | = 150.43                    | + 0.0594                        | * HWAVG3                    | + 0.7331                        | * TWAVG5                    | 0.58                           | -                               | 94.5%                       |
| H-15                                    | = 127.44                    | + 0.1326                        | * HWAVG3                    | + 0.6840                        | * TWAVG5                    | 0.49                           | -                               | 95.9%                       |
| H-16                                    | = 129.73                    | + 0.1527                        | * HWAVG3                    | + 0.6589                        | * TWAVG3                    | 0.65                           | -                               | 93.4%                       |
| H-17                                    | = 136.24                    | + 0.1259                        | * HWAVG3                    | + 0.6797                        | * TWAVG5                    | 0.51                           | -                               | 95.5%                       |
| H-18                                    | = 178.30                    | + 0.0819                        | * HWAVG3                    | + 0.6711                        | * TWAVG5                    | 0.74                           | -                               | 90.3%                       |
| H-19                                    | = 124.26                    | + 0.1388                        | * HWAVG3                    | + 0.6820                        | * TWAVG5                    | 0.68                           | -                               | 92.6%                       |
| H-20                                    | = 154.40                    | + 0.1096                        | * HWAVG3                    | + 0.6733                        | * TWAVG5                    | 0.61                           | -                               | 93.4%                       |
| H-21                                    | = 145.56                    | + 0.0950                        | * HWAVG3                    | + 0.7023                        | * TWAVG5                    | 0.60                           | -                               | 93.9%                       |
| H-22                                    | = 113.45                    | + 0.1101                        | * HWAVG3                    | + 0.7343                        | * TW4TO6                    | 1.62                           | -                               | 63.7%                       |
| H-25                                    | = 130.53                    | + 0.1486                        | * HWAVG3                    | + 0.6713                        | * TW4TO6                    | 1.33                           | -                               | 74.6%                       |

<sup>a</sup>MODEL:  $Y = A + B1 * (X1) + B2 * (X2).$

TABLE 11. SIMPLE LINEAR REGRESSION MODEL STATEMENTS FOR PIEZOMETERS

| -----MODEL STATEMENT <sup>a</sup> ----- |                          |                             |                        | MODEL STD.                     | MODEL STD.                      | COEFF.                      |
|-----------------------------------------|--------------------------|-----------------------------|------------------------|--------------------------------|---------------------------------|-----------------------------|
| PIEZOMETER HEAD<br>Y (ft)               | REGRESSION CONSTANT<br>A | REGRESSION COEFFICIENT<br>B | HW/TW<br>VARIABLE<br>X | ERROR OF<br>ESTIMATE<br>S (ft) | ERROR OF<br>ESTIMATE<br>S (psi) | OF<br>DETERMIN.<br>R-SQUARE |
| AU-1                                    | = -145.31                | + 1.1615                    | * HW10TO12             | 1.99                           | 0.86                            | 61.8%                       |
| AU-2                                    | = -43.97                 | + 1.0442                    | * HWAvg3               | 1.42                           | 0.61                            | 73.6%                       |
| AU-3                                    | = -94.56                 | + 1.1154                    | * HW                   | 0.93                           | 0.40                            | 88.0%                       |
| AE                                      | = 78.93                  | + 0.8823                    | * HWAvg30              | 1.95                           | 0.84                            | 47.3%                       |
| AD-1                                    | = 324.14                 | + 0.5637                    | * TWAVG3               | 1.05                           | 0.46                            | 75.9%                       |
| AD-2                                    | = 267.10                 | + 0.6394                    | * TWAVG10              | 1.27                           | 0.55                            | 62.0%                       |
| AD-3                                    | = 255.61                 | + 0.6547                    | * TWAVG10              | 2.39                           | 1.04                            | 32.6%                       |
| AD-4                                    | = 248.86                 | + 0.6634                    | * TWAVG3               | 1.41                           | 0.61                            | 70.7%                       |
| AD-5                                    | = 277.35                 | + 0.6218                    | * TWAVG5               | 0.88                           | 0.38                            | 83.1%                       |
| AD-6                                    | = 287.26                 | + 0.6105                    | * TWAVG5               | 0.87                           | 0.38                            | 82.6%                       |
|                                         |                          |                             |                        |                                |                                 |                             |
| BU-1                                    | = 134.89                 | + 0.7689                    | * HWAvg3               | 1.54                           | 0.67                            | 56.4%                       |
| BU-2                                    | = 635.06                 | + 0.1846                    | * HWAvg30              | 2.33                           | 1.01                            | 2.7%                        |
| BU-3                                    | = -3.17                  | + 1.0004                    | * HW                   | 1.35                           | 0.58                            | 73.8%                       |
| BE                                      | = 218.34                 | + 0.7093                    | * HW10TO12             | 1.13                           | 0.49                            | 65.4%                       |
| BD-1                                    | = 211.72                 | + 0.7194                    | * TWAVG10              | 1.12                           | 0.49                            | 72.7%                       |
| BD-2                                    | = 323.01                 | + 0.5691                    | * TWAVG5               | 1.80                           | 0.78                            | 49.2%                       |
| BD-3                                    | = 244.00                 | + 0.6677                    | * TWAVG10              | 0.73                           | 0.32                            | 84.5%                       |
| BD-4                                    | = 130.00                 | + 0.8243                    | * TWAVG10              | 2.00                           | 0.87                            | 52.3%                       |
| BD-5                                    | = 238.66                 | + 0.6781                    | * TWAVG5               | 0.81                           | 0.35                            | 87.2%                       |
| BD-6                                    | = 287.50                 | + 0.6107                    | * TWAVG10              | 0.94                           | 0.41                            | 73.3%                       |
|                                         |                          |                             |                        |                                |                                 |                             |
| CU-1                                    | = -99.59                 | + 1.1173                    | * HW                   | 1.55                           | 0.67                            | 72.7%                       |
| CU-2                                    | = -112.71                | + 1.1339                    | * HW                   | 1.69                           | 0.73                            | 69.8%                       |
| CU-3                                    | = 134.54                 | + 0.9121                    | * TW10TO12             | 2.16                           | 0.94                            | 46.7%                       |
| CE                                      | = 339.72                 | + 0.6147                    | * TW10TO12             | 2.18                           | 0.94                            | 28.1%                       |
| CD-1                                    | = 110.27                 | + 0.8522                    | * TWAVG30              | 1.16                           | 0.50                            | 71.9%                       |
| CD-2                                    | = 177.46                 | + 0.7606                    | * TWAVG3               | 1.64                           | 0.71                            | 70.1%                       |
| CD-3                                    | = 249.70                 | + 0.6640                    | * TWAVG3               | 0.72                           | 0.31                            | 90.3%                       |
| CD-4                                    | = 205.30                 | + 0.7225                    | * TWAVG3               | 1.05                           | 0.46                            | 83.7%                       |
| CD-5                                    | = 171.28                 | + 0.7661                    | * TWAVG5               | 1.22                           | 0.53                            | 79.3%                       |
| CD-6                                    | = 85.22                  | + 0.8840                    | * TWAVG10              | 0.71                           | 0.31                            | 90.8%                       |
|                                         |                          |                             |                        |                                |                                 |                             |
| DU-1                                    | = -104.21                | + 1.1162                    | * HW                   | 1.55                           | 0.67                            | 72.7%                       |
| DU-2                                    | = -56.97                 | + 1.0634                    | * HW                   | 2.34                           | 1.01                            | 51.4%                       |
| DD-1                                    | = 216.69                 | + 0.7079                    | * TWAVG3               | 1.17                           | 0.51                            | 79.9%                       |
| DD-2                                    | = 200.32                 | + 0.7283                    | * TWAVG3               | 0.86                           | 0.37                            | 88.7%                       |
| DD-4                                    | = 190.31                 | + 0.7403                    | * TWAVG5               | 1.35                           | 0.59                            | 74.4%                       |
| DD-5                                    | = -0.45                  | + 0.9939                    | * TWAVG10              | 6.11                           | 2.65                            | 14.6%                       |

TABLE 11 (CONTINUED)

| -----MODEL STATEMENT <sup>a</sup> ----- |                             |                                |                        |                                | MODEL STD.                      | MODEL STD.                  | COEFF. |
|-----------------------------------------|-----------------------------|--------------------------------|------------------------|--------------------------------|---------------------------------|-----------------------------|--------|
| PIEZOMETER HEAD<br>Y (ft)               | REGRESSION<br>CONSTANT<br>A | REGRESSION<br>COEFFICIENT<br>B | HW/TW<br>VARIABLE<br>X | ERROR OF<br>ESTIMATE<br>S (ft) | ERROR OF<br>ESTIMATE<br>S (psi) | OF<br>DETERMIN.<br>R-SQUARE |        |
| EU-1                                    | = 90.37                     | + 0.8827                       | * HW                   | 3.83                           | 1.66                            | 21.4%                       |        |
| EU-2                                    | = -11.69                    | + 1.0118                       | * HWA VG3              | 0.91                           | 0.40                            | 86.4%                       |        |
| EU-3                                    | = -38.72                    | + 1.0464                       | * HW                   | 0.69                           | 0.30                            | 92.1%                       |        |
| EE                                      | = 324.54                    | + 0.5798                       | * HWA VG3              | 0.83                           | 0.36                            | 71.7%                       |        |
| ED-1                                    | = 128.04                    | + 0.8331                       | * TWAVG10              | 1.02                           | 0.44                            | 81.2%                       |        |
| ED-2                                    | = 209.11                    | + 0.7120                       | * HW                   | 1.30                           | 0.56                            | 60.7%                       |        |
| ED-3                                    | = 309.73                    | + 0.5923                       | * HWA VG3              | 1.44                           | 0.62                            | 46.5%                       |        |
| ED-4                                    | = 411.72                    | + 0.4451                       | * TWAVG3               | 2.02                           | 0.87                            | 34.8%                       |        |
| ED-5                                    | = 119.52                    | + 0.8416                       | * TW4TO6               | 2.46                           | 1.06                            | 45.2%                       |        |
| ED-6                                    | = 763.86                    | + 0.0213                       | * TWAVG30              | 0.42                           | 0.18                            | 1.2%                        |        |
|                                         |                             |                                |                        |                                |                                 |                             |        |
| H-1                                     | = 266.05                    | + 0.6423                       | * TWAVG5               | 0.55                           | -                               | 93.0%                       |        |
| H-2                                     | = 294.86                    | + 0.6037                       | * TWAVG5               | 0.55                           | -                               | 92.2%                       |        |
| H-3                                     | = 280.86                    | + 0.6226                       | * TWAVG10              | 0.57                           | -                               | 88.6%                       |        |
| H-4                                     | = 281.18                    | + 0.6221                       | * TWAVG10              | 0.53                           | -                               | 90.0%                       |        |
| H-5                                     | = 270.67                    | + 0.6360                       | * TWAVG10              | 0.78                           | -                               | 81.3%                       |        |
| H-6                                     | = 245.73                    | + 0.6698                       | * TWAVG10              | 0.85                           | -                               | 80.2%                       |        |
| H-7                                     | = 309.83                    | + 0.5833                       | * TWAVG10              | 0.44                           | -                               | 92.0%                       |        |
| H-8                                     | = 206.69                    | + 0.7223                       | * TWAVG5               | 0.52                           | -                               | 95.0%                       |        |
| H-8A                                    | = 216.50                    | + 0.7091                       | * TWAVG5               | 0.50                           | -                               | 95.1%                       |        |
| H-9                                     | = 198.51                    | + 0.7332                       | * TWAVG5               | 0.62                           | -                               | 93.2%                       |        |
| H-10                                    | = 193.71                    | + 0.7398                       | * TWAVG5               | 0.57                           | -                               | 94.3%                       |        |
| H-11                                    | = 201.62                    | + 0.7291                       | * TWAVG5               | 0.51                           | -                               | 95.3%                       |        |
| H-12                                    | = 198.48                    | + 0.7332                       | * TWAVG5               | 0.52                           | -                               | 95.2%                       |        |
| H-13                                    | = 195.05                    | + 0.7378                       | * TWAVG5               | 0.59                           | -                               | 93.8%                       |        |
| H-14                                    | = 177.78                    | + 0.7613                       | * TWAVG5               | 0.59                           | -                               | 94.3%                       |        |
| H-15                                    | = 188.50                    | + 0.7468                       | * TWAVG5               | 0.54                           | -                               | 95.0%                       |        |
| H-16                                    | = 203.01                    | + 0.7272                       | * TWAVG3               | 0.70                           | -                               | 92.3%                       |        |
| H-17                                    | = 194.18                    | + 0.7393                       | * TWAVG5               | 0.55                           | -                               | 94.7%                       |        |
| H-18                                    | = 216.01                    | + 0.7100                       | * TWAVG5               | 0.75                           | -                               | 89.9%                       |        |
| H-19                                    | = 188.16                    | + 0.7477                       | * TWAVG5               | 0.71                           | -                               | 91.6%                       |        |
| H-20                                    | = 204.85                    | + 0.7252                       | * TWAVG5               | 0.64                           | -                               | 92.8%                       |        |
| H-21                                    | = 189.29                    | + 0.7473                       | * TWAVG5               | 0.62                           | -                               | 93.4%                       |        |
| H-22                                    | = 158.79                    | + 0.7937                       | * TW4TO6               | 1.62                           | -                               | 63.2%                       |        |
| H-25                                    | = 185.51                    | + 0.7599                       | * TW4TO6               | 1.33                           | -                               | 73.4%                       |        |

<sup>a</sup> MODEL:  $Y = A + B * (X)$ .

TABLE 12. COMPARISON OF REGRESSION MODELS FOR PIEZOMETERS

| PIEZOMETER | STANDARD ERROR OF ESTIMATE       |                                | COEFFICIENT OF DETERMINATION       |                                  |
|------------|----------------------------------|--------------------------------|------------------------------------|----------------------------------|
|            | MULTIPLE<br>REGRESSION<br>S (ft) | SIMPLE<br>REGRESSION<br>S (ft) | MULTIPLE<br>REGRESSION<br>R-SQUARE | SIMPLE<br>REGRESSION<br>R-SQUARE |
| AU-1       | 2.01                             | 1.99                           | 61.8%                              | 61.8%                            |
| AU-2       | 1.39                             | 1.42                           | 75.2%                              | 73.6%                            |
| AU-3       | 0.94                             | 0.93                           | 88.0%                              | 88.0%                            |
| AE         | 1.87                             | 1.95                           | 52.1%                              | 47.3%                            |
| AD-1       | 0.88                             | 1.05                           | 83.3%                              | 75.9%                            |
| AD-2       | 1.26                             | 1.27                           | 63.7%                              | 62.0%                            |
| AD-3       | 2.41                             | 2.39                           | 32.7%                              | 32.6%                            |
| AD-4       | 1.23                             | 1.41                           | 78.2%                              | 70.7%                            |
| AD-5       | 0.72                             | 0.88                           | 88.6%                              | 83.1%                            |
| AD-6       | 0.70                             | 0.87                           | 88.8%                              | 82.6%                            |
| BU-1       | 1.44                             | 1.54                           | 62.3%                              | 56.4%                            |
| BU-2       | 2.25                             | 2.33                           | 10.8%                              | 2.7%                             |
| BU-3       | 1.36                             | 1.35                           | 73.9%                              | 73.8%                            |
| BE         | 1.11                             | 1.13                           | 66.6%                              | 65.4%                            |
| BD-1       | 0.93                             | 1.12                           | 81.7%                              | 72.7%                            |
| BD-2       | 1.74                             | 1.80                           | 53.2%                              | 49.2%                            |
| BD-3       | 0.55                             | 0.73                           | 91.3%                              | 84.5%                            |
| BD-4       | 1.94                             | 2.00                           | 55.9%                              | 52.3%                            |
| BD-5       | 0.63                             | 0.81                           | 92.4%                              | 87.2%                            |
| BD-6       | 0.74                             | 0.94                           | 83.6%                              | 73.3%                            |
| CU-1       | 1.54                             | 1.55                           | 73.6%                              | 72.7%                            |
| CU-2       | 1.67                             | 1.69                           | 71.1%                              | 69.8%                            |
| CU-3       | 1.97                             | 2.16                           | 56.7%                              | 46.7%                            |
| CE         | 2.20                             | 2.18                           | 28.1%                              | 28.1%                            |
| CD-1       | 1.03                             | 1.16                           | 78.4%                              | 71.9%                            |
| CD-2       | 1.59                             | 1.64                           | 72.6%                              | 70.1%                            |
| CD-3       | 0.67                             | 0.72                           | 91.8%                              | 90.3%                            |
| CD-4       | 0.95                             | 1.05                           | 87.0%                              | 83.7%                            |
| CD-5       | 1.03                             | 1.22                           | 85.6%                              | 79.3%                            |
| CD-6       | 0.61                             | 0.71                           | 93.5%                              | 90.8%                            |
| DU-1       | 1.56                             | 1.55                           | 72.8%                              | 72.7%                            |
| DU-2       | 2.36                             | 2.34                           | 51.5%                              | 51.4%                            |
| DD-1       | 1.03                             | 1.17                           | 84.8%                              | 79.9%                            |
| DD-2       | 0.78                             | 0.86                           | 91.0%                              | 88.7%                            |
| DD-4       | 1.24                             | 1.35                           | 79.0%                              | 74.4%                            |
| DD-5       | 6.06                             | 6.11                           | 17.7%                              | 14.6%                            |

TABLE 12 (CONTINUED)

| PIEZOMETER | STANDARD ERROR OF ESTIMATE       |                                | COEFFICIENT OF DETERMINATION       |                                  |
|------------|----------------------------------|--------------------------------|------------------------------------|----------------------------------|
|            | MULTIPLE<br>REGRESSION<br>S (ft) | SIMPLE<br>REGRESSION<br>S (ft) | MULTIPLE<br>REGRESSION<br>R-SQUARE | SIMPLE<br>REGRESSION<br>R-SQUARE |
| EU-1       | 3.86                             | 3.83                           | 21.5%                              | 21.4%                            |
| EU-2       | 0.92                             | 0.91                           | 86.4%                              | 86.4%                            |
| EU-3       | 0.70                             | 0.69                           | 92.2%                              | 92.1%                            |
| EE         | 0.83                             | 0.83                           | 71.7%                              | 71.7%                            |
| ED-1       | 0.96                             | 1.02                           | 83.7%                              | 81.2%                            |
| ED-2       | 1.30                             | 1.30                           | 61.0%                              | 60.7%                            |
| ED-3       | 1.43                             | 1.44                           | 48.4%                              | 46.5%                            |
| ED-4       | 2.03                             | 2.02                           | 35.3%                              | 34.8%                            |
| ED-5       | 2.47                             | 2.46                           | 45.8%                              | 45.2%                            |
| ED-6       | 0.42                             | 0.42                           | 1.3%                               | 1.2%                             |
| H-1        | 0.46                             | 0.55                           | 95.2%                              | 93.0%                            |
| H-2        | 0.41                             | 0.55                           | 95.7%                              | 92.2%                            |
| H-3        | 0.41                             | 0.57                           | 94.1%                              | 88.6%                            |
| H-4        | 0.40                             | 0.53                           | 94.4%                              | 90.0%                            |
| H-5        | 0.65                             | 0.78                           | 87.4%                              | 81.3%                            |
| H-6        | 0.82                             | 0.85                           | 82.0%                              | 80.2%                            |
| H-7        | 0.39                             | 0.44                           | 94.0%                              | 92.0%                            |
| H-8        | 0.45                             | 0.52                           | 96.3%                              | 95.0%                            |
| H-8A       | 0.43                             | 0.50                           | 96.5%                              | 95.1%                            |
| H-9        | 0.59                             | 0.62                           | 94.1%                              | 93.2%                            |
| H-10       | 0.53                             | 0.57                           | 95.2%                              | 94.3%                            |
| H-11       | 0.45                             | 0.51                           | 96.4%                              | 95.3%                            |
| H-12       | 0.47                             | 0.52                           | 96.2%                              | 95.2%                            |
| H-13       | 0.57                             | 0.59                           | 94.4%                              | 93.8%                            |
| H-14       | 0.58                             | 0.59                           | 94.5%                              | 94.3%                            |
| H-15       | 0.49                             | 0.54                           | 95.9%                              | 95.0%                            |
| H-16       | 0.65                             | 0.70                           | 93.4%                              | 92.3%                            |
| H-17       | 0.51                             | 0.55                           | 95.5%                              | 94.7%                            |
| H-18       | 0.74                             | 0.75                           | 90.3%                              | 89.9%                            |
| H-19       | 0.68                             | 0.71                           | 92.6%                              | 91.6%                            |
| H-20       | 0.61                             | 0.64                           | 93.4%                              | 92.8%                            |
| H-21       | 0.60                             | 0.62                           | 93.9%                              | 93.4%                            |
| H-22       | 1.62                             | 1.62                           | 63.7%                              | 63.2%                            |
| H-25       | 1.33                             | 1.33                           | 74.6%                              | 73.4%                            |

regression model statements for piezometers, respectively. Table 12 provides a comparison between multiple and simple linear model performance indicators (R-SQUARE and S).

Spot-checks on the preceding results, obtained from the TVA mainframe computer, are shown in Figures 24 and 25. These show results of the SAS General Linear Models Procedure, as applied to two piezometers. Figure 24 shows the results of a multiple linear regression on standpipe H-1 while Figure 25 shows the results of a simple linear regression on pneumatic piezometer AD-2. These two piezometers were chosen randomly to illustrate results. In addition to parameter estimates and performance indicators (SAS refers to S as the ROOT MSE), a number of additional statistics are calculated by SAS in the General Linear Models Procedure. Some of these additional statistics relating to tests of significance and interval estimates are discussed in the following section.

The following are average values for key statistics from the regression models, summarized from Table 12 by model and instrument type:

| MODEL TYPE: | Multiple | Simple  | Multiple | Simple   |
|-------------|----------|---------|----------|----------|
| PARAMETER:  | S        | S       | R-SQUARE | R-SQUARE |
| PNEUMATIC:  | 1.46 ft  | 1.53 ft | 67 %     | 64 %     |
| STANDPIPE:  | 0.62 ft  | 0.67 ft | 92 %     | 90 %     |

The results show that, in general, more variation in head is explained for the standpipe piezometers than for the pneumatic piezometers (92% vs 67% for the multiple linear models). This result is consistent with the location of the standpipe piezometers and with the preceding

## GENERAL LINEAR MODELS PROCEDURE

## DEPENDENT VARIABLE INFORMATION

NUMBER OF OBSERVATIONS IN DATA SET = 59

NOTE: ALL DEPENDENT VARIABLES ARE CONSISTENT WITH RESPECT  
TO THE PRESENCE OR ABSENCE OF MISSING VALUES. HOWEVER,  
ONLY 58 OBSERVATIONS IN DATA SET CAN BE USED IN THIS  
ANALYSIS.

## GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: HM1 H-1

| SOURCE          | DF | SUM OF SQUARES | MEAN SQUARE  | F-VALUE | PR > F     | R-SQUARE | C.V.         |
|-----------------|----|----------------|--------------|---------|------------|----------|--------------|
| MODEL           | 2  | 233.20925609   | 116.60462805 | 549.29  | 0.0001     | 0.952322 | 0.0622       |
| ERROR           | 55 | 11.67557148    | 0.21228312   |         | ROOT MSE   |          | HM1 MEAN     |
| CORRECTED TOTAL | 57 | 244.88482757   |              |         | 0.46074192 |          | 741.25172414 |

| SOURCE | DF | TYPE I SS    | F VALUE | PR > F | DF | TYPE III SS | F-VALUE | PR > F |
|--------|----|--------------|---------|--------|----|-------------|---------|--------|
| HWAUG3 | 1  | 134.53693265 | 633.76  | 0.0001 | 1  | 5.42053167  | 25.53   | 0.0001 |
| TWAVG5 | 1  | 98.67232344  | 464.81  | 0.0001 | 1  | 98.67232344 | 464.81  | 0.0001 |

| PARAMETER | ESTIMATE     | T FOR HO:<br>PARAMETER=0 | PR > T | STD ERROR OF<br>ESTIMATE |
|-----------|--------------|--------------------------|--------|--------------------------|
| INTERCEPT | 183.37459090 | 8.39                     | 0.0001 | 21.86634916              |
| HWAUG3    | 0.17959762   | 5.05                     | 0.0001 | 0.03554163               |
| TWAVG5    | 0.55725762   | 21.56                    | 0.0001 | 0.02584735               |

NOTE: SAS INSTITUTE, SAS CIRCLE, BOX 8000, CARY, N.C. 27511-8000

FIGURE 24. SAS PRINTOUT<sup>a</sup> FOR MULTIPLE LINEAR REGRESSION ON STANDPIPE PIEZOMETER H-1<sup>a</sup>Retyped printout from TVA mainframe computer.

## GENERAL LINEAR MODELS PROCEDURE

## DEPENDENT VARIABLE INFORMATION

NUMBER OF OBSERVATIONS IN DATA SET = 59

## GENERAL LINEAR MODELS PROCEDURE

DEPENDENT VARIABLE: ADM2 AD-2

| SOURCE          | DF | SUM OF SQUARES | MEAN SQUARE  | F-VALUE | PR > F     | R-SQUARE | C.V.         |
|-----------------|----|----------------|--------------|---------|------------|----------|--------------|
| MODEL           | 1  | 150.95925341   | 150.95925341 | 93.01   | 0.0001     | 0.620016 | 0.1721       |
| ERROR           | 57 | 92.51701778    | 1.62310558   |         | ROOT MSE   |          | ADM2 MEAN    |
| CORRECTED TOTAL | 58 | 243.47627118   |              |         | 1.27401161 |          | 740.18474576 |

| SOURCE  | DF | TYPE I SS    | F VALUE | PR > F | DF | TYPE III SS  | F-VALUE | PR > F |
|---------|----|--------------|---------|--------|----|--------------|---------|--------|
| TWAVG10 | 1  | 150.95925341 | 93.01   | 0.0001 | 1  | 150.95925341 | 93.01   | 0.0001 |

| PARAMETER | ESTIMATE     | T FOR HO:<br>PARAMETER=0 | PR > T | STD ERROR OF<br>ESTIMATE |
|-----------|--------------|--------------------------|--------|--------------------------|
| INTERCEPT | 267.10665860 | 5.45                     | 0.0001 | 49.05449733              |
| TWAVG10   | 0.63943297   | 9.64                     | 0.0001 | 0.06630382               |

NOTE: SAS INSTITUTE, SAS CIRCLE, BOX 8000, CARY, N.C. 27511-8000

FIGURE 25. SAS PRINTOUT<sup>a</sup> FOR SIMPLE LINEAR REGRESSION ON PNEUMATIC PIEZOMETER AD-2<sup>a</sup>Retyped printout from TVA mainframe computer.

correlation analysis. On the average, the percent of explained variation (R-SQUARE) for the multiple linear models was only 2-3% greater than R-SQUARE for the simple linear models (67% vs 64% for pneumatic piezometers and 92% vs 90% for standpipe piezometers). Addition of the second predictor reduced model standard error of estimates by 4.5% for pneumatic piezometers (1.46 ft vs 1.53 ft) and 7.5% for standpipe piezometers (0.62 ft vs 0.67 ft).

Table 13 compares key model performance indicators for pneumatic piezometers by range and designation:

TABLE 13. COMPARISON OF PNEUMATIC PIEZOMETER MULTIPLE REGRESSION MODEL RESULTS BY DESIGNATION AND RANGE

| PIEZOMETER<br>DESIGNATION/RANGE | S<br>(ft) | R-SQUARE<br>(%) |
|---------------------------------|-----------|-----------------|
| U-1                             | 2.08      | 58.4            |
| U-2                             | 1.72      | 59.0            |
| U-3                             | 1.24      | 77.7            |
| E                               | 1.51      | 54.7            |
| D-1                             | 0.97      | 82.4            |
| D-2                             | 1.33      | 68.3            |
| D-3                             | 1.27      | 66.0            |
| D-4                             | 1.48      | 67.1            |
| D-5                             | 2.18      | 66.0            |
| D-6 <sup>a</sup>                | 0.68      | 88.6            |
| A                               | 1.34      | 71.2            |
| B                               | 1.27      | 67.2            |
| C                               | 1.32      | 73.8            |
| D                               | 2.17      | 66.1            |
| E <sup>a</sup>                  | 1.61      | 60.7            |

<sup>a</sup>Excluding ED-6.

Average values for multiple regression model R-SQUARE by range, as shown in Table 13, varied from 60.7% (range E) to 73.8% (range C). These differences reflect varying seepage path geometries and material properties at the five instrumented locations. Comparison of model results by designation shows that, in general, model performance was best for piezometers located at point D-6 (average R-SQUARE = 88.6%). This is logical because of their location within permeable gravels in close proximity to Watts Bar Reservoir. Models for designation E (located in the less permeable cutoff trench fill) had the lowest average coefficient of determination (average R-SQUARE = 54.7%). Inferences based on designation are further limited by the wide range in performance of individual models.

#### IV.4.2.2 Statistical Inference

Two central topics in statistical inference are interval estimates and tests of significance. According to Kleinbaum and Kupper, interval estimates are concerned with estimating a probable set of values for a parameter of interest, while tests of significance investigate whether parameter estimates differ enough from hypothesized values to conclude that a null hypothesis is true (23:26). In both cases, the sample distribution is compared with a theoretical distribution.

This section is concerned with statistical inferences that can be made on the piezometric data, based on comparison of sample data with the Student's *t* distribution. The *t* distribution is commonly used to determine interval estimates and perform tests of significance.

According to Kleinbaum and Kupper, this distribution is appropriate for describing the behavior of any random variable that is approximately normally distributed (23:21). According to Younger, the  $t$  distribution represents an alternative to the normal distribution, modified because the population standard deviation is unknown and must be estimated by the sample standard deviation (62:198). Additional information on the  $t$  distribution is provided in the Appendix, Section A.6.

#### IV.4.2.2.1 Tests of Significance

As previously stated, tests of significance investigate whether parameter estimates differ enough from hypothesized values to conclude that a null hypothesis is true. This is of particular interest in testing the strength of model predictors. Since the primary purpose of this analysis is to characterize the relationship between observed piezometric head and headwater-tailwater time averages, it is appropriate to test the strength of model predictors. However, according to Snedecor and Cochran, a significance test should not be considered the sole criteria for accepting or rejecting a given hypothesis (40:28). This assertion is compatible with the following procedure for testing statistical null hypotheses, as given by Kleinbaum and Kupper (23:26):

1. Check the assumptions concerning the properties of the underlying variables being measured, in order to justify the use of the testing procedure being used.
2. State the null hypothesis  $H_0$  and the alternative hypothesis  $H_1$ .
3. Specify the significance level  $\alpha$ .
4. Specify the test statistic to be used and its distribution under  $H_0$ .
5. Specify the acceptance and acceptance regions for the test.

6. Compute the value of the test statistic from the observed data.
7. Draw conclusions concerning rejection or nonrejection of  $H_0$ .

In this analysis, tests of significance are proposed for regression model parameters, based on the following null hypotheses:

$$H_0: a = 0 \quad \text{and} \quad H_0: b_i = 0 ,$$

where

$a$  = regression constant (intercept), and

$b_i$  = regression coefficient associated with the  $i$ th predictor variable.

The alternate hypotheses corresponding to the above are:

$$H_1: a \neq 0 \quad \text{and} \quad H_1: b_i \neq 0 .$$

According to Younger, the significance level ( $\alpha$ ) is the probability of rejecting  $H_0$  when  $H_0$  is, in fact, true (62:211). Conversely, the degree of confidence (D.C.) that  $H_1$  is true (or  $H_0$  is false) can be expressed as:

$$\text{D.C.} = 100\% (1 - \alpha) . \quad (33)$$

An alternate method for significance testing involves first calculating the test statistic for the parameter of interest and comparing this with the critical region of the test distribution to obtain a significance level  $\alpha$  at which  $H_0$  would be rejected. This is the approach that will be taken for this study, since prespecification of a

significance level implies an application of results. According to Kleinbaum and Kupper, the approach quantifies exactly how unusual the observed results are if  $H_0$  were true (23:28). This is the method used by SAS (Figures 24 and 25, pp. 113 and 114). Adjacent to parameter estimates on these printouts are t statistics for  $H_0$ : parameter = 0 and significance levels at which  $H_0$  would be rejected ( $P > |T|$ ). For the case of the models in Figures 24 and 25, parameters are significant at a minimum level of 0.001, implying a greater than a 99.9% degree of confidence that a relationship exists between the recorded piezometric head recorded and the HW/TW variables selected.

In most cases, the objective in significance testing of regression coefficients is to be able to reject the null hypothesis, establishing a high degree of confidence that independent and dependent variables are related. An exception in this case is the significance of headwater variables in models predicting head for downstream piezometers. In this case, it is desirable to reject the alternative hypothesis (that recorded heads and headwater variables are related), because optimum performance of the grout curtain is intended to decrease the connectivity of the basal sand and gravels and bedrock cavities, thus decreasing the effect of headwater fluctuations at downstream locations.

For this analysis, a check on the assumption of normality will be made in order to justify significance testing.

#### IV.4.2.2.1.1 The Normality Assumption

Application of interval estimates and tests of significance are based on the assumption that the scatter of error around the regression equation is normally distributed. Younger (62:19(4)) lists the relationships that exist for all normal distributions:

- approximately 68% of the values lie within one standard deviation of their mean
- approximately 95% of the values lie within two standard deviations of their mean
- approximately 99% of the values lie within three standard deviations of their mean

According to Snedecor and Cochran, the possible single most important reason that the normality assumption is used is that under a wide variety of conditions, the distribution of sample averages tends to become normal with increasing sample size, even if the distribution of the population is not normal (40:35). This condition follows from the Central Limit theorem. The topic of normality is further discussed in the Appendix, Section A.5.

Probability distributions were determined for the Tellico piezometer data and compared with the criteria for normal distributions. This method, described by Younger as the method of standardized residuals, provides a rough method of comparing sample distributions with the normal distribution (62:294). For each piezometer, the distribution of error about the multiple regression model was computed. The percent of values falling within 1, 2, and 3 estimated standard deviations (S), from the value predicted by the regression equation, was determined. Detailed results are provided in Appendix Table A-2. In order to summarize the results of this test, a comparison was made between the

composite error distribution for multiple linear regression models (all piezometers) and the normal distribution. The results of this comparison are as follows:

| Standard deviations from mean  | 1   | 2   | 3   |
|--------------------------------|-----|-----|-----|
| *Normal Distribution           | 68% | 95% | 99% |
| *Composite Sample Distribution | 76% | 95% | 99% |

\*Percent of values within given range.

Figure 26 shows the computed composite multiple linear regression model error distribution for the piezometric data in comparison with the normal distribution. This figure shows that the composite sample of all piezometric data has a roughly symmetrical bell-shaped distribution about the multiple regression models, and that a larger proportion of sample residuals lie within one estimated standard deviation of the regression equations than for the normal distribution. However, the two distributions correspond more closely at higher percentiles of the probability distribution. As predicted by the Central Limit theorem, Appendix Table A-2 shows greater deviation of individual model error distribution from the normal in comparison with the larger composite distribution for all models. Appendix Figures A-1 and A-2, which show individual model error distribution for piezometers AD-2 and H-1, show this tendency.

A second check on the normality assumption is provided by the chi-square goodness of fit test. In this test, a numerical index based on the square of differences between observed error distribution and the standard normal is computed and compared with a theoretical chi-square

# STANDARDIZED RESIDUALS--ALL PIEZOMETERS

MULTIPLE LINEAR REGRESSION MODELS

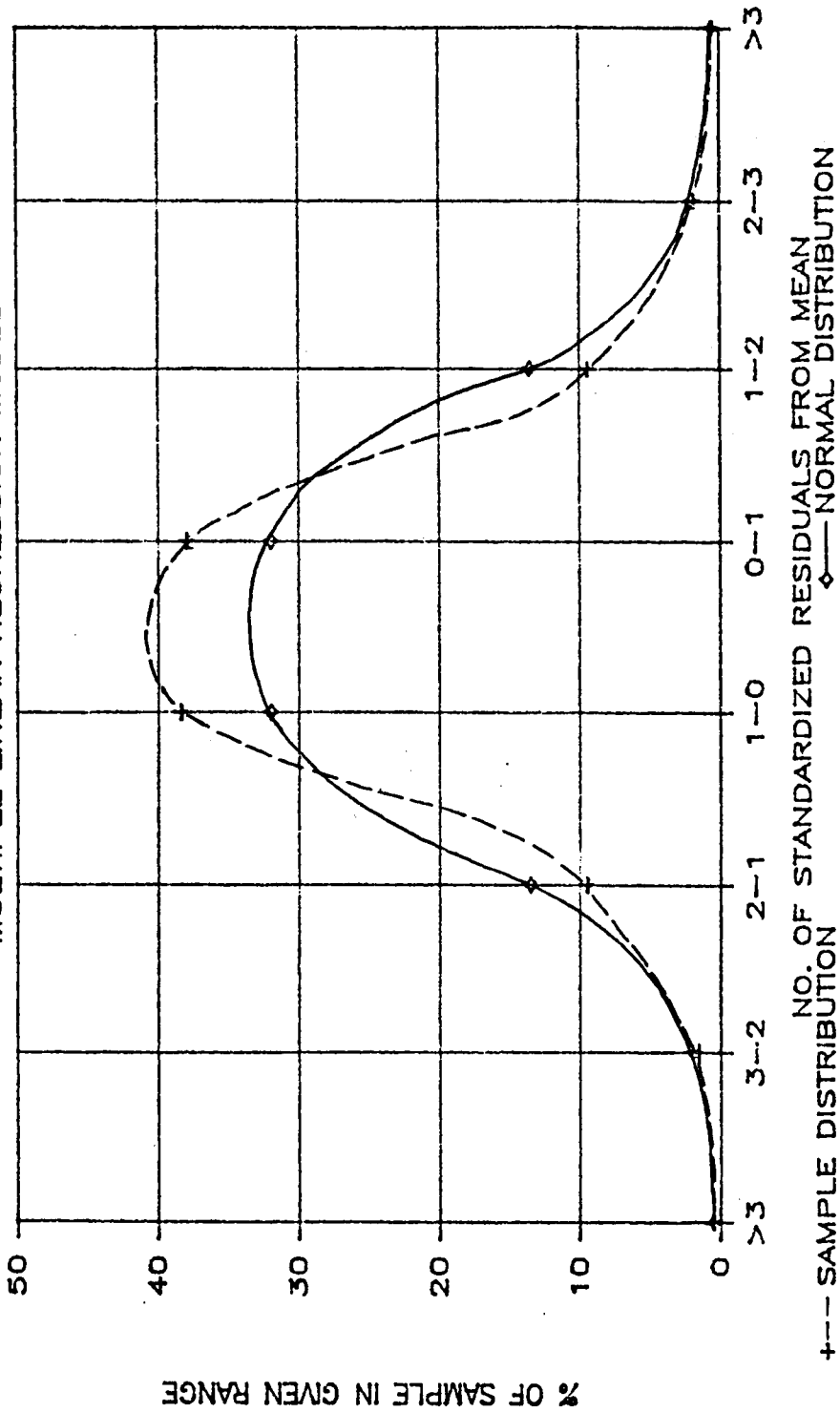


FIGURE 26. COMPARISON OF THE COMPOSITE ERROR DISTRIBUTION FOR MULTIPLE REGRESSION MODELS WITH THE STANDARD NORMAL

distribution. A description of this test is presented in the Appendix, Section A.7. Test results for multiple regression models are shown in Appendix Table A-3. Test results indicate that, on the average, the degree of confidence that individual multiple regression model error distributions are normal is only 10-25%.

Both methods of testing normality indicate deviations between multiple linear regression model error distributions for the piezometric data and the standard normal. However, the composite error distribution for all piezometers closely approximates the normal distribution in the significance range commonly specified for most regression problems ( $\alpha = 0.01 - 0.05$ ). The chi-square test is biased by differences in the two distributions between 0 and 1 standard deviation. A greater percentage of regression model residuals falls within 0-1 standard deviation of the mean (predicted) value than for the normal distribution--this is a favorable condition, in terms of the accuracy of estimation.

The conclusion reached regarding the assumption of normality for the subject piezometric models is that the error distribution sufficiently approximates the standard normal to justify tests of significance on model parameters using the t statistic. According to Younger, as long as the data assumes a "reasonably symmetric mound-shaped distribution" that is not too far from the normal, probabilities associated with the theoretical t distribution will be "reasonably applicable" to the calculated test statistic (62:293). Kleinbaum and Kupper also recommend that "considerable leeway" be given when deciding whether the normality

assumption can be made for a regression analysis (23:44). Also, as pointed out by Younger,  $t$  values can be used subjectively to test whether a variable is a strong predictor even if the data is not normally distributed (62:293).

#### IV.4.2.2.1.2 $t$ statistics for Regression Model Parameters

The possibility of testing for the significance of the regression constant was first mentioned in Section IV.4.1.1 with reference to comparison of the regression models stated in Equ's. 26 and 27. As discussed by Younger, failure to reject the hypothesis  $H_0: a = 0$  would provide some justification for use of a zero-intercept model (62:220). Testing involves calculating the  $t$  statistic (formula given in the Appendix, Section A.8) and comparing this with a theoretical  $t$  distribution.

Hypothesis tests on regression coefficients are important to the regression problem because they test the relationship between the dependent variable  $Y$  and model predictor variables. Younger asserts that the significance of model predictor variables is the central question in any regression study, since it only makes sense to make estimates and measure model error if there is a reasonable degree of confidence that a relationship exists (62:209). Significance tests on model coefficients are accomplished by testing the null hypothesis  $H_0: b_i = 0$ , which implies that there is no relationship between the associated predictor variable  $X_i$  and the dependent variable  $Y$ . In this case, the significance level  $\alpha$  can be interpreted as the probability of concluding

that a relationship between  $X_i$  and  $Y$  exists when there is no relationship in the population. As with tests on the regression constant, testing involves calculating the  $t$  statistic (formula given in the Appendix, Section A.8) and comparing this with a theoretical  $t$  distribution.

The effect of multicorrelation in multiple linear regression on the standard errors of the regression coefficients was previously discussed in Section IV.4.1.1. Since multicorrelation of predictor variables causes large standard errors of associated regression coefficients,  $t$  values as calculated by Equ. A-12 in this case would be close to zero. As pointed out by Younger,  $H_0$  is then only rejected if a predictor variable affects the dependent variable strongly enough to overcome multicorrelation effects (62:354).

Results of the significance tests are presented in Appendix Tables A-4 through A-6. Table A-4 lists standard errors, calculated  $t$  statistics, and the degree of confidence that  $H_0$  can be rejected (D.C.) for simple linear regression model parameters. Table A-5 lists standard errors for multiple linear regression model constants and coefficients. Table A-6 lists  $t$  statistics and D.C. for the multiple linear regression model parameters.

Results of the  $t$  tests for model parameters give information of the significance of the predictors. These statistics are more easily interpreted for the case of the simple linear regression models, where multicorrelation effects are absent. Table A-4 indicates that, with the exception of piezometers ED-6, BU-2, and DD-5, the single headwater/tailwater predictor variables are significant at a minimum level of

$\alpha = 0.001$ . This implies that there is a greater than 99.9% probability that a relationship exists between the piezometric response and the respective HW/TW predictor variables selected. Table A-4 also shows the regression constants for simple linear models to be significant at a minimum level of  $\alpha = 0.001$  for 24 of the 46 pneumatic piezometers and 22 of the 24 standpipe piezometers modeled. Intercept terms were significant at a minimum level of  $\alpha = 0.5$  for all but 5 of the models, indicating that, in general, inclusion of the intercept in the models is appropriate.

The following is a summary of average standard errors of the regression model parameters reported in Tables A-4 and A-5, by model and instrument type:

| MODEL TYPE: | Simple  | Multiple | Simple  | Multiple | Multiple |
|-------------|---------|----------|---------|----------|----------|
| STATISTIC:  | Sa      | Sa       | Sb      | Sb1      | Sb2      |
| PNEUMATIC:  | 62.6 ft | 72.5 ft  | 0.08 ft | 0.11 ft  | 0.10 ft  |
| STANDPIPE:  | 23.4 ft | 30.6 ft  | 0.03 ft | 0.05 ft  | 0.04 ft  |

A general increase (on the order of 30%) in standard errors of the regression constants and coefficients for the multiple models over the simple models are due to multicorrelation. On the average this increase is not considered excessive, being less than an order of magnitude.

Results of t tests for multiple linear regression parameters (Table A-6) show that both predictors are significant at a level below  $\alpha = 0.001$  (D.C. > 99.9%) for 16 of the 46 pneumatic piezometers and 12 of the 24 standpipe piezometers modeled. Since, as discussed,  $H_0$  is only rejected if a predictor variable affects the dependent variable strongly

enough to overcome multicorrelation effects, the results of Table A-6 provide a conservative estimate of the D.C..

#### IV.4.2.2.2 Interval Estimates

As previously stated, interval estimates are concerned with estimating a probable set of values for a parameter of interest. They can be applied to both regression model parameters and to values of the dependent variable Y.

According to Kleinbaum and Kupper, a confidence interval (CI) is bounded by two points between which there is a given level of confidence that a population parameter lies (23:23). According to Snedecor and Cochran, confidence intervals apply only to the population that was actually sampled, and caution should be used regarding claims that such inferences apply to a more extensive population (40:16).

Confidence intervals using the t distribution have the following general form:

$$CI = \left( \begin{array}{c} \text{point estimate} \\ \text{of parameter} \end{array} \right) \pm \left( \begin{array}{c} \text{percentile} \\ \text{of the} \\ \text{t distribution} \end{array} \right) \left( \begin{array}{c} \text{standard} \\ \text{error of} \\ \text{estimate} \end{array} \right) . \quad (34)$$

Individual model confidence intervals are not presented herein. However, in order to estimate the general order of magnitude of these statistics, a 99% confidence interval is applied to the mean multiple regression model standard error of estimate for the pneumatic and standpipe piezometers. The following result is obtained:

| PIEZ. TYPE | S avg   | t(0.01,56) | 99% CI             |
|------------|---------|------------|--------------------|
| PNEUMATIC  | 1.46 ft | 2.67       | ± 3.9 ft (1.6 psi) |
| STANDPIPE  | 0.62 ft | 2.67       | ± 1.6 ft           |

It can therefore be established that the 99% confidence interval for multiple regression models is on the order of ±3.9 ft for pneumatic and ±1.6 ft. for standpipe piezometers.

Caution should be used in the interpretation and application of individual model confidence intervals. A significance level must be established a priori, based on specific intended application of results. Also, these statistics are too often applied to other populations than those from which they are computed. Confidence intervals computed from one sample of the piezometric data could not be extended to future observations, because of time-dependent effects inherent in the seepage regime being studied. Additionally, results of the normality testing indicate that deviations in individual model error distributions from the standard normal limit the interpretation of confidence intervals.

In order to classify extreme values for further discussion, observations falling outside of individual multiple regression model 99% confidence intervals are listed in Table 14. Table 14 lists 70 observations from 52 piezometers that fell outside of these intervals. This procedure does not necessarily classify the observations as erroneous--unexplained variations may be the result of model error.

TABLE 14. OBSERVATIONS FALLING OUTSIDE OF MULTIPLE REGRESSION MODEL 99% CONFIDENCE INTERVALS

| OBSERVED PREDICTED |                 |              |              |                    | OBSERVED PREDICTED |                 |              |              |                    |
|--------------------|-----------------|--------------|--------------|--------------------|--------------------|-----------------|--------------|--------------|--------------------|
| PIEZOMETER         | DATE<br>(y/m/d) | HEAD<br>(ft) | HEAD<br>(ft) | DIFFERENCE<br>(ft) | PIEZOMETER         | DATE<br>(y/m/d) | HEAD<br>(ft) | HEAD<br>(ft) | DIFFERENCE<br>(ft) |
| AU-1               | 84/03/19        | 798.6        | 792.9        | 5.7                | EU-1               | 82/01/25        | 792.0        | 803.6        | -11.6              |
| AU-3               | 81/05/19        | 814.7        | 811.8        | 2.9                | EU-2               | 83/04/25        | 807.0        | 810.8        | -3.8               |
| AU-3               | 83/06/22        | 814.7        | 811.7        | 3.0                | EU-2               | 83/06/22        | 813.9        | 810.6        | 3.3                |
| AU-3               | 83/11/28        | 810.6        | 808.0        | 2.6                | EU-3               | 84/08/20        | 813.8        | 811.7        | 2.1                |
| AE                 | 84/04/25        | 784.9        | 793.9        | -9.0               | EE                 | 83/11/28        | 796.5        | 793.8        | 2.7                |
| AD-2               | 82/06/15        | 736.9        | 740.9        | -4.0               | ED-4               | 84/02/24        | 732.4        | 739.3        | -6.9               |
| AD-2               | 83/01/26        | 745.0        | 738.9        | 6.1                | ED-5               | 83/09/20        | 727.6        | 742.9        | -15.3              |
| AD-3               | 83/01/26        | 755.9        | 739.0        | 16.9               | ED-6               | 82/08/26        | 782.8        | 779.7        | 3.1                |
| AD-4               | 83/01/26        | 729.9        | 736.5        | -6.6               | DU-1               | 83/09/20        | 807.4        | 803.2        | 4.2                |
| AD-5               | 84/04/25        | 736.3        | 738.3        | -2.0               | DU-2               | 82/11/22        | 798.5        | 804.9        | -6.4               |
| AD-6               | 83/01/26        | 738.5        | 736.4        | 2.1                | DD-1               | 83/06/22        | 745.0        | 741.7        | 3.3                |
| BU-1               | 82/09/27        | 755.4        | 759.5        | -4.1               | DD-4               | 83/06/22        | 742.7        | 739.3        | 3.4                |
| BU-1               | 82/10/21        | 754.7        | 759.3        | -4.6               | DD-5               | 84/08/20        | 716.8        | 737.5        | -20.7              |
| BU-3               | 82/05/17        | 806.0        | 809.8        | -3.8               | DD-5               | 84/12/20        | 709.7        | 730.7        | -21.0              |
| BU-3               | 82/06/15        | 806.0        | 809.9        | -3.9               | DD-5               | 85/01/25        | 707.8        | 730.4        | -22.6              |
| BD-1               | 83/06/22        | 748.1        | 745.5        | 2.6                | H-4                | 81/04/14        | 739.8        | 740.9        | -1.1               |
| BD-2               | 83/02/17        | 753.7        | 743.2        | 10.5               | H-5                | 83/12/23        | 737.6        | 740.7        | -3.1               |
| BD-4               | 83/06/22        | 747.4        | 741.4        | 6.0                | H-6                | 83/09/20        | 736.8        | 741.9        | -5.1               |
| BD-4               | 84/03/19        | 743.0        | 736.8        | 6.2                | H-7                | 81/04/14        | 739.5        | 740.7        | -1.2               |
| BD-4               | 84/08/20        | 749.7        | 742.0        | 7.7                | H-8                | 84/11/28        | 738.4        | 739.7        | -1.3               |
| BD-6               | 81/03/18        | 738.7        | 736.5        | 2.2                | H-8A               | 85/01/25        | 737.3        | 738.6        | -1.3               |
| CU-1               | 82/02/17        | 799.4        | 804.0        | -4.6               | H-9                | 84/11/28        | 737.2        | 739.6        | -2.4               |
| CU-2               | 82/07/22        | 813.9        | 808.6        | 5.3                | H-10               | 84/11/28        | 737.6        | 739.7        | -2.1               |
| CU-3               | 82/02/17        | 821.3        | 810.1        | 11.2               | H-10               | 85/01/25        | 737.0        | 738.4        | -1.4               |
| CE                 | 80/08/14        | 788.6        | 794.8        | -6.2               | H-13               | 84/11/28        | 737.4        | 739.5        | -2.1               |
| CE                 | 82/02/17        | 805.9        | 796.9        | 9.0                | H-14               | 84/11/28        | 737.4        | 739.5        | -2.1               |
| CD-1               | 84/05/11        | 740.9        | 743.8        | -2.9               | H-15               | 85/01/25        | 737.0        | 738.4        | -1.4               |
| CD-1               | 84/05/30        | 742.1        | 744.9        | -2.8               | H-16               | 85/01/25        | 735.4        | 737.9        | -2.5               |
| CD-2               | 83/09/20        | 734.4        | 741.1        | -6.7               | H-18               | 84/01/30        | 741.2        | 738.3        | 2.9                |
| CD-2               | 84/08/20        | 736.3        | 742.0        | -5.7               | H-18               | 84/03/19        | 740.9        | 738.6        | 2.3                |
| CD-4               | 83/06/22        | 743.9        | 741.1        | 2.8                | H-19               | 84/06/20        | 744.7        | 742.1        | 2.6                |
| CD-5               | 82/04/21        | 734.2        | 737.3        | -3.1               | H-19               | 84/07/24        | 745.1        | 743.0        | 2.1                |
| CD-6               | 84/03/19        | 737.7        | 736.1        | 1.6                | H-20               | 84/01/30        | 740.6        | 738.4        | 2.2                |
| CD-6               | 84/05/11        | 748.8        | 746.8        | 2.0                | H-22               | 83/12/23        | 740.3        | 746.0        | -5.7               |
| EU-1               | 81/12/17        | 792.0        | 803.6        | -11.6              | H-22               | 84/01/30        | 749.6        | 742.9        | 6.7                |

#### IV.4.2.3 Plots of Observed vs Predicted Values

Plots of observed vs predicted values provide an important means of assessing trends, determining reasons for lack of model performance, etc. Plots of this type for the pneumatic piezometers are included, since, in general, model performance was more variable than for the standpipe piezometers. As with the data plots presented in Section IV.2, straight lines have been drawn between successive values in order to assist in interpretation--it is not implied that either the data or predicted values are continuous. These plots conclude the presentation of regression analysis results. Further discussion of these results will be provided in Section V.

#### IV.5 Flow Net Analysis

In this section, flow nets are fitted to instrumented ranges A-E. The construction of flow nets represents the culmination of many seepage analyses, since knowledge of section geometry and material properties, assessment of data, and engineering judgement must be integrated to produce solutions. For this research, flow net construction is undertaken to provide a graphical representation of the conditions previously modeled by regression, thus complementing the interpretation of statistical results.

For the purposes of this research, the sections have been considerably simplified in order to effect solutions. The technique employed involves first constructing equipotential contours onto each section utilizing the piezometric data and then fitting flow lines to these

contours. Because the flow nets are fitted to data as well as assumed boundary conditions, model error should be expected, since a heterogeneous flow system is being modeled as a simplified homogeneous section.

The solutions obtained will be used to contrast the results obtained by regression, corroborate hypotheses concerning general flow conditions in the bedrock and provide an estimate of discharge under the embankment.

#### IV.5.1 Observed Potential

The subject piezometric data are utilized in the following analysis by application of steady-flow equations. It is appropriate, therefore, to restate the derived expression for hydraulic head at a point in porous media for steady-flow, as depicted in Figure 23 (p. 97):

$$h = HW - K_e(HW - TW) , \quad (25)$$

where

$h$  = hydraulic head,

$HW$  = headwater elevation,

$TW$  = tailwater elevation, and

$K_e$  = energy dissipation factor.

As discussed in Section IV.4.1.1, the quantity  $K_e$  is the normalized fraction of reservoir operating head dissipated along a pathline upstream from a given point in a flow system. It is useful to rearrange Equ. 25 to produce an expression for  $K_e$ :

$$K_e = \frac{(HW - h)}{(HW - TW)} = \frac{(HW - h)}{H} . \quad (35)$$

This expression provides a calculating formula for  $K_e$ . As with the previous regression models, The fixed quantities HW and TW are replaced by the headwater/tailwater time averages correlating most strongly with the respective piezometers. These variables are then used with recorded piezometric heads to calculate  $K_e$  for each individual observation. The denominator of Equ. 35 becomes the differential between the headwater and tailwater variables selected--the "effective" reservoir operating head.

As seen in the summary of published piezometric monitoring analyses, piezometric heads have been expressed as a potential, representing the fraction of reservoir operating head dissipated in pore fluid at the instrumented location ( $K_e$ ). The normalized flow potential ( $P_e$ ) is related to the energy dissipation factor  $K_e$  by the following:

$$P_e = (1 - K_e) . \quad (36)$$

In practice, average values of  $P_e$  for the data are computed. Results of the calculations for  $P_e$  and  $K_e$  are given in Table 15. In cases where  $K_e$  was calculated as greater than 1,  $P_e$  was set to zero. Ideally, erroneous observations should be deleted before calculation--however, this procedure is neglected because of sample size. The assumption is that mean values are not significantly affected by erroneous individual observations in this case.

TABLE 15. AVERAGE FLOW POTENTIAL RECORDED BY PIEZOMETERS

| PIEZOMETER | HEADWATER<br>VARIABLE<br>X1 | TAILWATER<br>VARIABLE<br>X2 | AVERAGE FLOW<br>DISSIPATED<br>Ke | POTENTIAL <sup>a</sup><br>AVAILABLE<br>Pe |
|------------|-----------------------------|-----------------------------|----------------------------------|-------------------------------------------|
| AU-1       | HW10T012                    | TWAVG30                     | 20.2%                            | 80%                                       |
| AU-2       | HWAVG3                      | TWAVG10                     | 11.5%                            | 89%                                       |
| AU-3       | HW                          | TWAVG30                     | 1.4%                             | 99%                                       |
| AE         | HWAVG30                     | TWAVG30                     | 23.2%                            | 77%                                       |
| AD-1       | HWAVG3                      | TWAVG3                      | 98.1%                            | 2%                                        |
| AD-2       | HWAVG3                      | TWAVG10                     | 99.5%                            | 0%                                        |
| AD-3       | HWAVG3                      | TWAVG10                     | 99.8%                            | 0%                                        |
| AD-4       | HWAVG3                      | TWAVG3                      | 100.3%                           | 0%                                        |
| AD-5       | HWAVG3                      | TWAVG5                      | 103.6%                           | 0%                                        |
| AD-6       | HWAVG3                      | TWAVG5                      | 101.3%                           | 0%                                        |
|            |                             |                             |                                  |                                           |
| BU-1       | HWAVG3                      | TWAVG5                      | 73.9%                            | 26%                                       |
| BU-2       | HWAVG30                     | TW10T012                    | 36.7%                            | 63%                                       |
| BU-3       | HW                          | TWAVG30                     | 4.0%                             | 96%                                       |
| BE         | HW10T012                    | TWAVG30                     | 24.5%                            | 76%                                       |
| BD-1       | HWAVG3                      | TWAVG10                     | 94.2%                            | 6%                                        |
| BD-2       | HWAVG10                     | TWAVG5                      | 94.1%                            | 6%                                        |
| BD-3       | HWAVG3                      | TWAVG10                     | 102.6%                           | 0%                                        |
| BD-4       | HWAVG3                      | TWAVG10                     | 100.0%                           | 0%                                        |
| BD-5       | HWAVG3                      | TWAVG5                      | 99.3%                            | 1%                                        |
| BD-6       | HWAVG3                      | TWAVG10                     | 100.8%                           | 0%                                        |
|            |                             |                             |                                  |                                           |
| CU-1       | HW                          | TWAVG30                     | 6.3%                             | 94%                                       |
| CU-2       | HW                          | TWAVG30                     | 5.9%                             | 94%                                       |
| CU-3       | HW10T012                    | TW10T012                    | 2.3%                             | 98%                                       |
| CE         | HWAVG30                     | TW10T012                    | 23.1%                            | 77%                                       |
| CD-1       | HWAVG10                     | TWAVG30                     | 98.7%                            | 1%                                        |
| CD-2       | HWAVG3                      | TWAVG3                      | 99.5%                            | 0%                                        |
| CD-3       | HWAVG3                      | TWAVG3                      | 98.5%                            | 2%                                        |
| CD-4       | HWAVG3                      | TWAVG3                      | 100.0%                           | 0%                                        |
| CD-5       | HWAVG3                      | TWAVG5                      | 102.5%                           | 0%                                        |
| CD-6       | HWAVG3                      | TWAVG10                     | 100.9%                           | 0%                                        |
|            |                             |                             |                                  |                                           |
| DU-1       | HW                          | TWAVG30                     | 14.1%                            | 86%                                       |
| DU-2       | HW                          | TWAVG3                      | 7.8%                             | 92%                                       |
| DD-1       | HWAVG3                      | TWAVG3                      | 99.2%                            | 1%                                        |
| DD-2       | HWAVG3                      | TWAVG3                      | 101.0%                           | 0%                                        |
| DD-4       | HWAVG3                      | TWAVG5                      | 102.6%                           | 0%                                        |
| DD-5       | HW10T012                    | TWAVG10                     | 107.0%                           | 0%                                        |

TABLE 15 (CONTINUED)

| PIEZOMETER | HEADWATER<br>VARIABLE<br>X1 | TAILWATER<br>VARIABLE<br>X2 | AVERAGE FLOW<br>DISSIPATED<br>Ke | POTENTIAL <sup>a</sup><br>AVAILABLE<br>Pe |
|------------|-----------------------------|-----------------------------|----------------------------------|-------------------------------------------|
| EU-1       | HW                          | TWAVG30                     | 6.6%                             | 93%                                       |
| EU-2       | HWAVG3                      | TWAVG30                     | 3.0%                             | 97%                                       |
| EU-3       | HW                          | TWAVG30                     | 1.6%                             | 98%                                       |
| EE         | HWAVG3                      | TWAVG30                     | 22.8%                            | 77%                                       |
| ED-1       | HWAVG3                      | TWAVG10                     | 93.6%                            | 6%                                        |
| ED-2       | HW                          | TWAVG30                     | 34.3%                            | 66%                                       |
| ED-3       | HWAVG3                      | TWAVG30                     | 29.4%                            | 71%                                       |
| ED-4       | HWAVG5                      | TWAVG3                      | 98.4%                            | 2%                                        |
| ED-5       | HWAVG3                      | TW4T06                      | 96.8%                            | 3%                                        |
| ED-6       | HW4T06                      | TWAVG30                     | 43.9%                            | 56%                                       |
| H-1        | HWAVG3                      | TWAVG5                      | 98.0%                            | 2%                                        |
| H-2        | HWAVG3                      | TWAVG5                      | 97.7%                            | 2%                                        |
| H-3        | HWAVG3                      | TWAVG10                     | 97.8%                            | 2%                                        |
| H-4        | HWAVG3                      | TWAVG10                     | 97.8%                            | 2%                                        |
| H-5        | HWAVG3                      | TWAVG10                     | 98.2%                            | 2%                                        |
| H-6        | HWAVG3                      | TWAVG10                     | 98.0%                            | 2%                                        |
| H-7        | HWAVG3                      | TWAVG10                     | 97.9%                            | 2%                                        |
| H-8        | HWAVG3                      | TWAVG5                      | 98.3%                            | 2%                                        |
| H-8A       | HWAVG3                      | TWAVG5                      | 98.2%                            | 2%                                        |
| H-9        | HWAVG3                      | TWAVG5                      | 98.4%                            | 2%                                        |
| H-10       | HWAVG3                      | TWAVG5                      | 98.3%                            | 2%                                        |
| H-11       | HWAVG3                      | TWAVG5                      | 98.4%                            | 2%                                        |
| H-12       | HWAVG3                      | TWAVG5                      | 98.5%                            | 2%                                        |
| H-13       | HWAVG3                      | TWAVG5                      | 98.6%                            | 1%                                        |
| H-14       | HWAVG3                      | TWAVG5                      | 98.4%                            | 2%                                        |
| H-15       | HWAVG3                      | TWAVG5                      | 98.3%                            | 2%                                        |
| H-16       | HWAVG3                      | TWAVG3                      | 98.4%                            | 2%                                        |
| H-17       | HWAVG3                      | TWAVG5                      | 98.2%                            | 2%                                        |
| H-18       | HWAVG3                      | TWAVG5                      | 98.0%                            | 2%                                        |
| H-19       | HWAVG3                      | TWAVG5                      | 97.9%                            | 2%                                        |
| H-20       | HWAVG3                      | TWAVG5                      | 97.8%                            | 2%                                        |
| H-21       | HWAVG3                      | TWAVG5                      | 96.8%                            | 3%                                        |
| H-22       | HWAVG3                      | TW4T06                      | 91.3%                            | 9%                                        |
| H-23       | HWAVG3                      | TWAVG3                      | 104.4%                           | 0%                                        |
| H-24       | HWAVG3                      | TWAVG3                      | 78.9%                            | 21%                                       |
| H-25       | HWAVG3                      | TW4T06                      | 89.0%                            | 11%                                       |

<sup>a</sup> As defined on p. 132.

#### IV.5.2 Solutions for Idealized Sections

Flow nets for the five instrumented ranges are presented in Figures 27-31. Discussion is limited to an explanation of the boundary conditions and material properties selected for each section. Discharges associated with the sections analyzed are also presented and compared.

For the following, only flow through the calcareous bedrock and overlying basal gravel layer is modeled. These strata are estimated to have hydraulic conductivities several orders of magnitude greater than the alluvial clays and silts or the embankment fill--flow can therefore be assumed to occur primarily through these units. This assumption is consistent with the instrumentation concept, which seeks to assess grout curtain performance and monitor uplift pressures near the downstream toe.

##### IV.5.2.1 Range A

A simplified flow net for range A is presented in Figure 27. Hydrostatic pressures are assumed to exist at the interface between the basal sands and gravels and overlying silty units. The grout curtain is modeled as a zone of reduced hydraulic conductivity extending 75 ft below the cutoff trench to an impermeable boundary. Flow through the embankment is not modeled.

Assigning assumed values of hydraulic conductivity to the bedrock and utilization of the properties of flow nets enables the computation

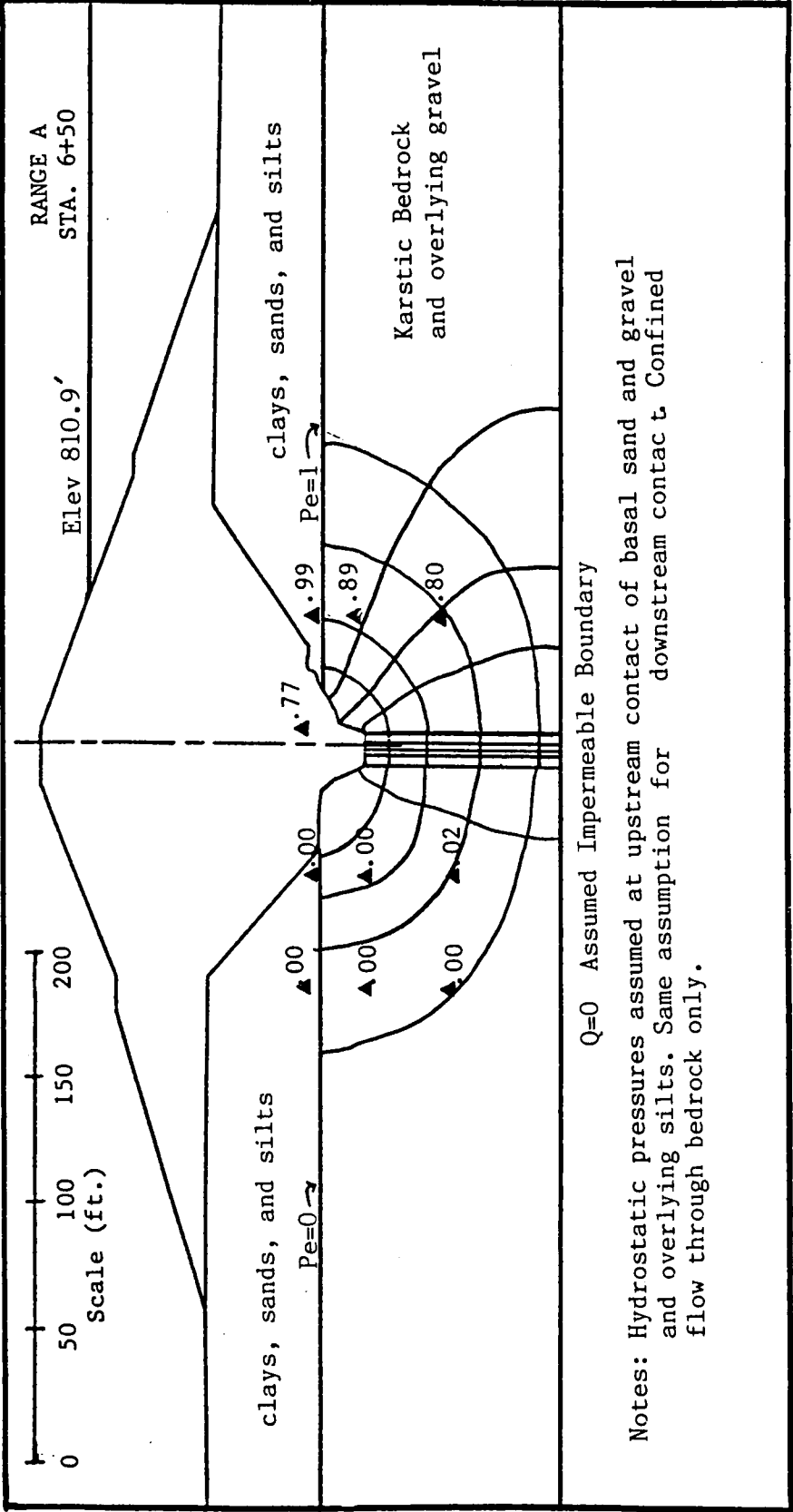


FIGURE 27. FLOW NET FOR RANGE A

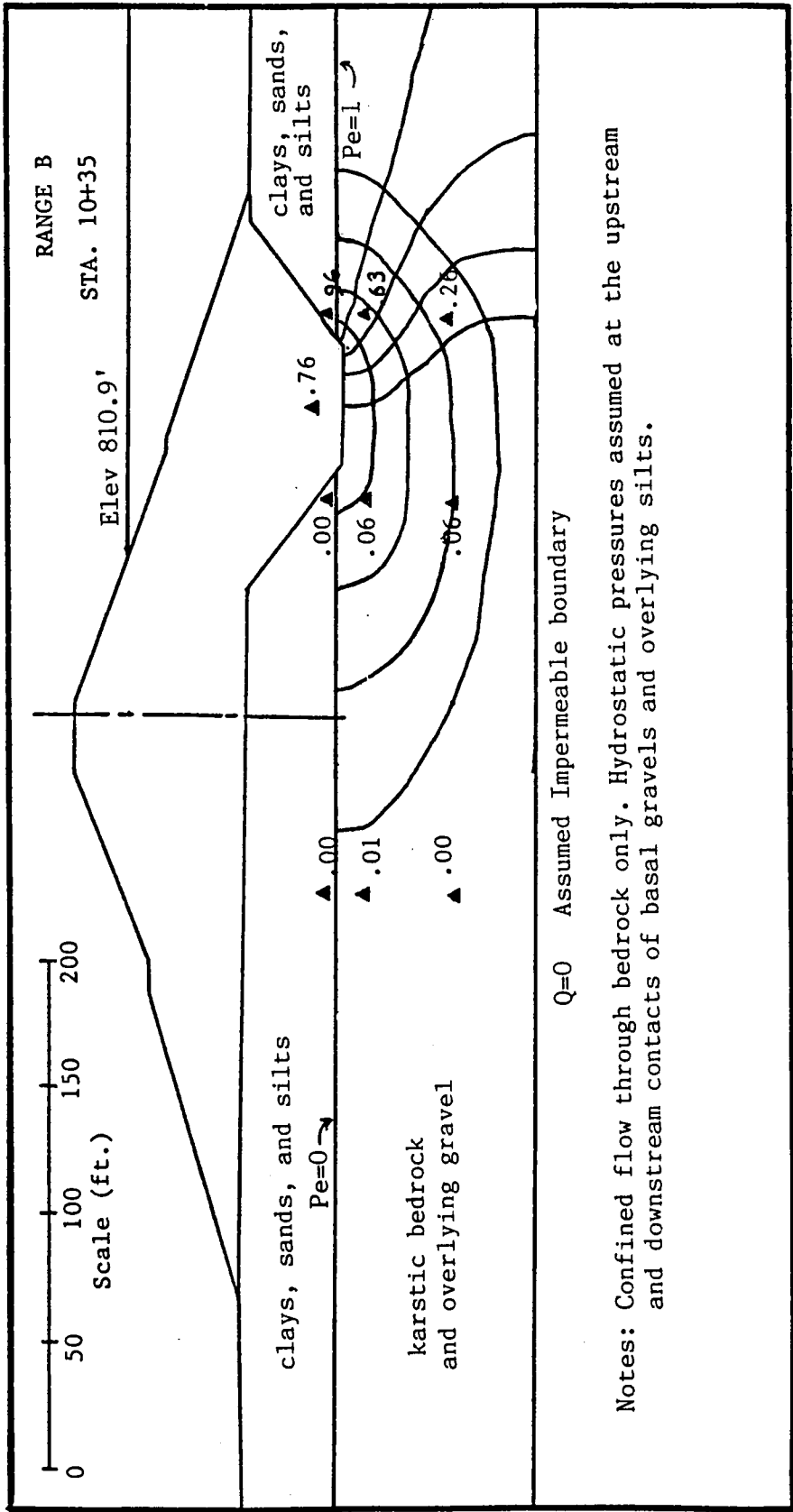


FIGURE 28. FLOW NET FOR RANGE B

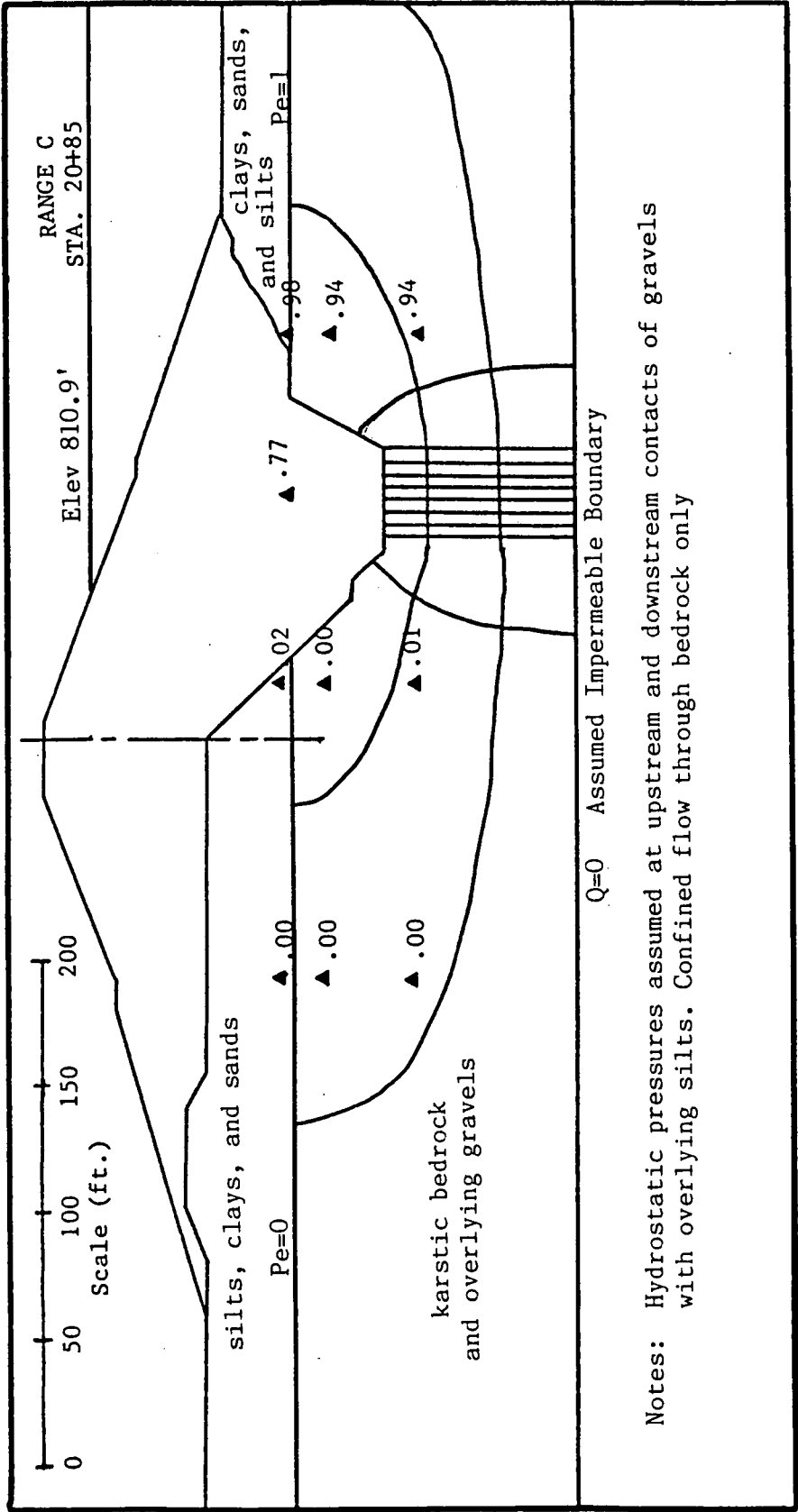


FIGURE 29. FLOW NET FOR RANGE C

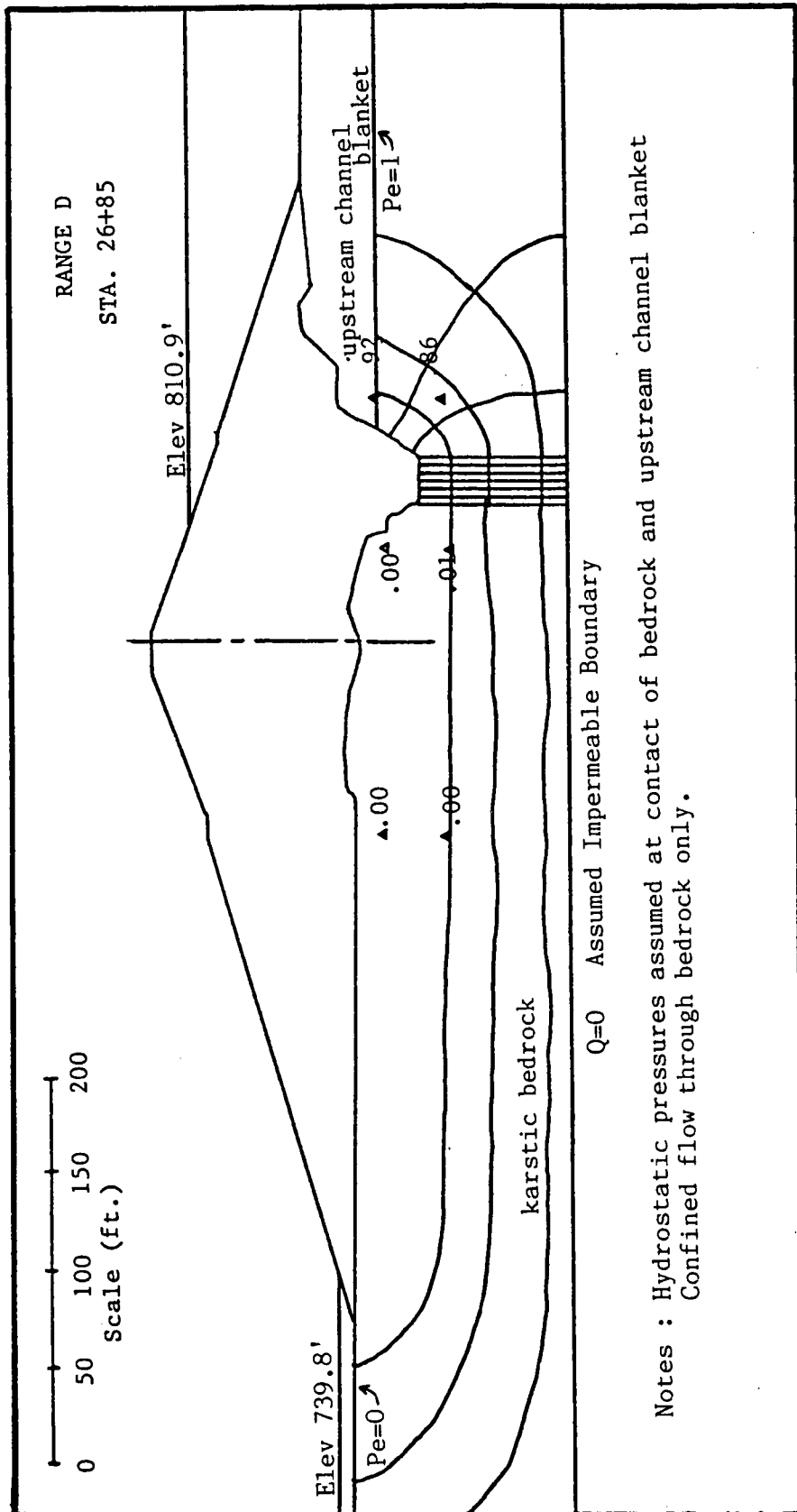


FIGURE 30. FLOW NET FOR RANGE D

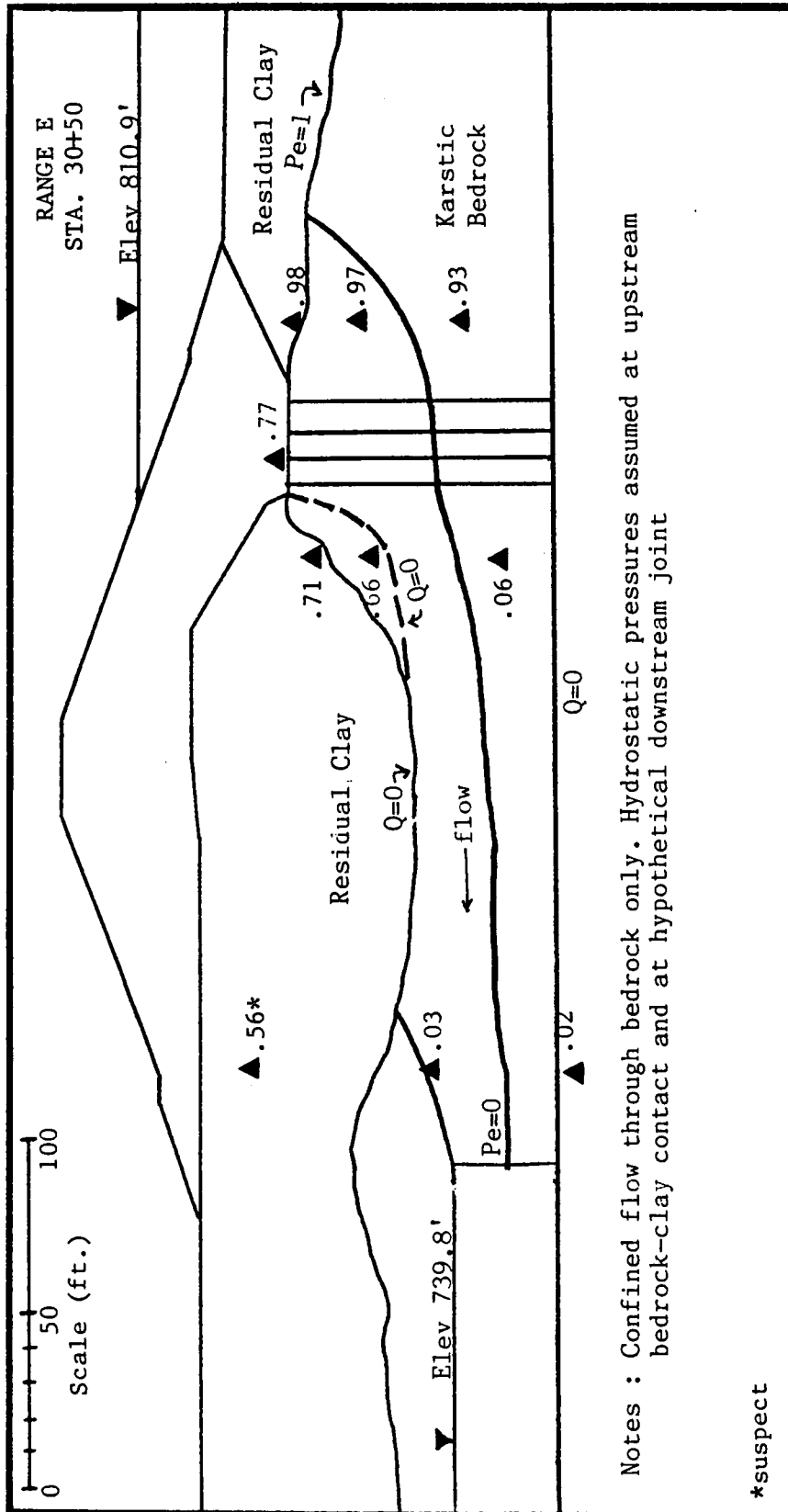


FIGURE 31. FLOW NET FOR RANGE E

of a rough estimate for the flow modeled in Figure 27. The hydraulic conductivity of the calcareous bedrock is obviously difficult to define--this is evidenced by the lack of any published values in the TVA investigations researched. The hydraulic conductivity of this strata is assumed to be  $1.0\text{E-}2$  cm/s, an average value for karst limestone given in Freeze and Cherry (13:29). The discussion of results will address the question of sensitivity in this estimate. The hydraulic conductivity of the grouted zone is estimated by assuming horizontal flow through the upstream bedrock-grout curtain interface and then applying a coordinate transformation involving flow through materials of hydraulic conductivity  $K_1$  and  $K_2$ :

$$\left(\frac{d_2}{d_1}\right) = \left(\frac{K_2}{K_1}\right)^{1/2}, \quad (37)$$

where

$d_2/d_1$  = ratio of distances between equipotential lines along a common pathline between materials 1 and 2.

Let material 1 be the karstic bedrock and material 2 be the grouted zone. From Figure 27, the quantity  $d_2/d_1$  is estimated to be  $1/10$ , which enables the following estimate of  $K_2$ , the hydraulic conductivity of the grouted zone:

$$K_2 = K_1 \left(\frac{d_2}{d_1}\right)^2 = 1.0\text{E-}2\text{cm/s} (1/10)^2 = 1.0\text{E-}4 \text{ cm/s}$$

This computed value ( $K_2 = 1.0E-4$  cm/s) roughly coincides with the lower limit of permeabilities for karst limestone reported in Freeze and Cherry (13:29). The flow per unit width ( $q$ ) underneath the embankment for range A is estimated using Equ. 14. The total head loss through the system ( $H$ ) is first estimated as a mean effective operating head:

$$H = (HW - TW_{AVG3})_{avg.} = (810.9' - 739.8') = 71.12' .$$

Equ. 14 is then used to calculate flow as:

$$q = K H \frac{Nf}{Nt} = \frac{(1.0E-2 \text{ cm/s})(71.12')}{10 (30.48 \text{ cm})} \frac{4.25 (1 \text{ ft})}{1} ,$$

$$= 9.9E-3 \text{ cfs/ft.}$$

#### IV.5.2.2 Range B

A simplified flow net for range B is presented in Figure 28. As for range A, hydrostatic pressures are assumed along an idealized interface between the basal gravel and overlying silt, flow through the embankment is not modeled, and an impervious boundary is assumed at a depth of 75 ft below the cutoff trench. Unlike Range A, potentials recorded by piezometers upstream of the grout curtain show a greater dissipation of head in this zone. This condition follows logically from the observed character of bedrock in this section, which was found to be "tighter" (fewer joints and cavities) during exploration and construction than other localities. Assuming the hydraulic conductivity of the

strata in this section to be  $1.0\text{E-}3$  cm/s, the flow per unit width under the embankment is estimated using using Equ. 14 as:

$$q = K H \frac{Nf}{Nt} = \frac{(1.0\text{E-}3)(71.12')}{5} \frac{5 (1/30.48)}{5} ,$$

$$= 2.33\text{E-}3 \text{ cfs/ft.}$$

#### IV.5.2.3 Range C

A simplified flow net for range C is presented in Figure 29. The boundary conditions and material properties assumed for this section are the same as those used for range A. Using Equ. 14, the flow per unit width under the embankment is estimated as:

$$q = K H \frac{Nf}{Nt} = \frac{(1.0\text{E-}2)(71.12')}{10} \frac{3 (1/30.48)}{10} ,$$

$$= 7.00\text{E-}3 \text{ cfs/ft.}$$

#### IV.5.2.4 Range D

A simplified flow net for Range D is presented in Figure 30. The boundary conditions and material properties assumed for this section are similar to those used for range A (soil profiles are not present at this section). Using Equ. 14, the flow per unit width under the embankment is estimated as:

$$q = K H \frac{Nf}{Nt} = \frac{(1.0\text{E-}2)(71.1')}{10} \frac{3.25 (1/30.48)}{10} ,$$

$$= 8.17\text{E-}3 \text{ cfs/ft.}$$

## IV.5.2.5 Range E

A simplified flow net for range E is presented in Figure 31. Range E instruments a complex zone of strata on the right abutment, and flow conditions at this section appear to deviate substantially from those in the previous 4 sections. Most notable are the higher flow potentials recorded by piezometers ED-2 and ED-3 than those at similar locations in the other sections. Geologic sections and borings show a thick deposit of residual silty clay overlying bedrock downstream of the cutoff trench instead of the basal sands and gravels found at the other locations. Reported hydraulic conductivity values (see Appendix Table A-1) for this type of residuum were on the order of  $1.0\text{E-}6$  cm/s. On the assumption that flow is occurring predominantly through the more porous karst limestone, only flow through the bedrock is modeled. Hydrostatic conditions are assumed at the interface of bedrock with alluvium upstream of the cutoff trench. Hydrostatic conditions corresponding to mean tailwater are assumed along a hypothesized joint plane downstream of the cutoff trench. The resulting discharge corresponding to the system modeled is calculated using Equ. 14 as:

$$q = K H \frac{N_f}{N_t} = \frac{(1.0\text{E-}2\text{cm/s})(71.12') (2) (1/30.48)}{5} ,$$

$$= 9.34\text{E-}3 \text{ cfs/ft.}$$

## IV.5.2.6 Summary of Computed Discharges

Table 16 lists and summarizes discharge calculations for instrumented sections A-E. The unit discharges computed for the sections analyzed

ranged from a maximum of  $9.92\text{E-}3$  cfs (Range A) to a minimum of  $2.33\text{E-}3$  cfs (Range B) and averaged  $7.35\text{E-}3$  cfs. Multiplication of this average discharge by the embankment length (2700 ft) yields an estimated total discharge (Q) underneath the embankment of  $Q = 20$  cfs. This represents 0.35% of the estimated mean annual streamflow at the site (5700 cfs). A discussion of the flow net analysis will be provided in Section 5.

TABLE 16. DISCHARGE CALCULATIONS FROM FLOW NETS<sup>a</sup>

| RANGE          | K<br>(cm/s) | Nf   | Nd | H<br>(ft)    | q<br>(cfs/ft)   |
|----------------|-------------|------|----|--------------|-----------------|
| A              | 1.0E-02     | 4.25 | 10 | 71.1         | 9.92E-03        |
| B              | 1.0E-03     | 5    | 5  | 71.1         | 2.33E-03        |
| C              | 1.0E-02     | 3    | 10 | 71.1         | 7.00E-03        |
| D              | 1.0E-02     | 3.5  | 10 | 71.1         | 8.17E-03        |
| E              | 1.0E-02     | 2    | 5  | 71.1         | <u>9.34E-03</u> |
| Mean Unit Flow |             |      |    | q = 7.35E-03 |                 |

<sup>a</sup>Discharge through foundation bedrock as modeled in Figures 24-28.

## V. CONCLUSIONS

The data presented and analyzed is the result of the most extensive piezometric monitoring system currently in place at TVA hydroprojects. The system was carefully conceived prior to construction by TVA engineers and approved by a team of expert consultants. In keeping with the scope of this research, important conclusions regarding the performance of the dam and foundation will be left to the TVA design staff and more experienced engineers. The primary emphasis will be to discuss possible applications and limitations of the statistical modeling and to interpret the results in terms of the physical system modeled. The implications of this research are relevant where they contribute, on a project-specific basis or generally, to the goals of monitoring for dam safety.

Caution must be used in drawing conclusions from statistical analyses of dam engineering problems--this is particularly true in the design phase. In assessing causes for the failure of Teton Dam, R. Curry (57:5) gave the following expert testimony:

the principal human cause . . . of failure . . . was very poor site selection coupled with an inadequate empirically based engineering-geologic approach to design and construction.

In assessing the use of probabalistic risk analysis for dam design, Ralph Peck cautions that it could be dangerous if it diminishes "design for defense in depth" regarding the risk of subsurface erosion and piping (56:11).

The analysis presented herein is fundamentally different from probabalistic design methods mentioned by Mr. Curry and Mr. Peck. In

general, the objectives of modeling are to (1) describe a phenomenon, and (2) to predict behavior. From the preceding remarks, it is clear that a potential for failure of dam exists if statistical models are used to predict the value of critical design parameters (such as pore pressures). The principal purpose of the modeling done herein relates to the first modeling objective--to describe.

### V.1 Correlation Analysis

The correlation analysis provided important initial information on the strength of association between observed piezometric heads and headwater/tailwater elevations. The analysis corroborated visual evidence of trends seen in the plots, and showed the effect of time on piezometric response (within the limitations of the HW/TW variables selected). Correlation results are generally consistent with the locations of the piezometers within the respective sections. Since the piezometer layout was designed to monitor water pressures in rock joints and pervious gravels (with the exception of designation E in the cutoff trench), strong correlation with HW/TW variables would seem to indicate that most of the instruments are functioning as intended. As discussed in Section IV.2, correlation coefficients can be evaluated in relation to known or inferred conditions to substantiate field evidence and/or hypotheses. A similar conclusion was drawn in the analysis by Epifanov et al. (9:428), based on correlation analyses.

As developed herein, the correlation analysis was utilized primarily to assist in formulating regression models. Here, strong correlation

between recorded piezometric heads and the HW/TW variables selected provided the basis for further analysis and justification for the use of linear models (since  $r$  measures the strength of linear association between variables).

## V.2 Regression Analysis

In general, the regression analysis indicates that a substantial amount of variation in piezometric head recorded by the piezometers can be explained by headwater and tailwater fluctuations (average R-SQUARE = 67% for pneumatic piezometers and 92% for standpipe piezometers). Since no published results of this type were encountered, model performance relative to other projects cannot be assessed. However, model performance can be assessed on the basis of the information obtained and possible applications.

Of central interest in the regression analysis are sources of error. Because erroneous data could be misinterpreted, it is critical to identify such erroneous data at the earliest possible opportunity. As discussed in Section VI.4, error in regression may be classified as model error and random error.

The regression analysis results indicate that model error is indeed present, and in some cases, is substantial. An evaluation of the plots of observed vs predicted values shows both trends and exceptions for model performance among the respective piezometer groupings. Model error can indicate that assumptions made in model formulation are

inappropriate--piezometers for which model error is obvious are therefore of interest.

Model error is obvious in the cases of piezometers located in the cutoff trench (designation E), as expected. Plots of observed vs predicted values for piezometers AE, BE, CE, and EE (Appendix Figures A-6, A-16, A-26, and A-44 respectively) show the tendency for a gradual increase in head with time. The regression models for these instruments therefore tend to underpredict heads in the first half of the sampling period and overpredict in the second half. As discussed, this increase is thought to be due to the effects of pore fluid compression.

Model error for piezometers at points U-1 and U-2 is characterized by a tendency to underpredict at higher values of head and overpredict at lower values. This trend is illustrated by the performance of the model for AU-1 (see Appendix Figure A-3). This condition is thought to be due to the simplified representation of headwater/tailwater fluctuations by time-averages.

Model error is also apparent in the case of piezometer BU-2, where the headwater/tailwater time-averages presented are not effective in describing the seemingly erratic variations recorded. Appendix Figure A-14 shows the transient nature of head recorded at this piezometer, resulting in model error. Higher heads recorded in the earlier time portion of the sample are thought to be a delayed response to initial filling. It is inferred that since decline of higher heads caused by filling, this piezometer responds to the delayed effect of rapid

headwater and tailwater fluctuations, as caused by hydrologic events. Comparison of the time difference between the date of special data observations for the May 1984 flood (May 11) and the maximum head recorded for piezometer BU-2 subsequent to flooding (789.40 ft on August 20) yields a time lag on the order of 100 days.

A significant contribution to model error is thought to be the simplification of antecedent headwater and tailwater elevations into HW/TW variables. Plots of daily midnight elevations (Figures 10 and 11, pp. 70 and 71 , show short-term fluctuations in elevation--these are not adequately described by time averages of midnight elevations. The daily elevations are in turn, only a sample of continuous headwater and tailwater time functions. Because variations in hydraulic head with time are obviously a function of headwater-tailwater variations ( $\partial h / \partial t \neq 0$ ), model error results from simplification of the diffusion equation (Equ. 9) into LaPlace's equation (Equ. 10).

Another source of model error comes from neglecting velocity differential to simplify Bernoulli's equation (Equ. 6) into the expression for hydraulic head (Equ. 7). However, this contribution should be considered negligible. The average flow velocity calculated from the results of the TVA dye test (0.14 ft/s, see p. 22) yields a velocity head of only  $3.0 \times 10^{-4}$  ft. Velocities several orders of magnitude greater than this would still yield negligible velocity heads. However, velocities of this magnitude would cause model error with regard to the applicability of Darcy's Law.

The applicability of Darcy's law should be questioned in a problem involving karst bedrock, as found at the Tellico project. In model formulation, it was acknowledged that this law may not be fully applicable. Darcy's law provided a simple solution upon which regression and flow net modeling could be based. The conclusion reached regarding the use of this assumption is that it has been justified, based on the model results.

The second category of error associated with the modeling is random error. This category includes instrument malfunctions and reading errors. Values such as the maximum reported for piezometer CU-3 (see Appendix Figure A-25) of 821.3 ft are thought to fall in this category. Sources of error include blockage and/or leakage of the piezometer bypass valve and tube lines, malfunction of the external pressure gage or nitrogen tank valve, and transcription errors.

Examination of the plot for piezometer DD-5 (Appendix Figure A-38) indicates substantial deviation from predicted behavior beginning in the later portion of the sampling period. As discussed, the minimum for this piezometer after the erratic decline shown was 707.8 ft. A gage malfunction is likely, since the minimum was approximately 25 ft lower than the tailwater elevation at this time. A possible explanation is the introduction of particulate matter into the piezometer chamber between the diaphragm and the bypass valve (see Figure 7, p. 33). This would allow bypass to occur at lower pressures.

The tabulation of values falling outside of multiple regression model 99% confidence intervals (Table 14, p. 129) lists extreme values

resulting from both model error and random error. It is not possible in all cases to differentiate between the two types of error. Observations deviating from the models by a large amount (on the order of 10 ft or more) are thought to be the result of random error--smaller errors are more difficult to classify.

In many cases, comparison of multiple and simple linear models indicates only modest improvement of performance indicators (S and R-SQUARE) by addition of a second predictor variable. In several cases (12 pneumatic piezometers), model standard error of estimates actually increased with addition of the second predictor variable (see Table 12, p. 110). This condition follows from the calculating formula for S (Equ. A-6). Each time a parameter is added to the model, a degree of freedom is lost, decreasing the denominator of the calculating formula for S. If the added predictor variable is unsuccessful in explaining additional variation in the independent variable, then the result is an increase in S. In some cases, therefore, the hydrostatic model (simple linear) is more appropriate for describing the piezometric heads than the steady flow model (multiple linear). In most cases, however, comparison of model performance indicates both a modest increase in R-SQUARE and a modest decrease in S by addition of the second predictor variable. The inference to be made from these results is that flow is occurring through the foundation, but that this flow has been considerably reduced by the seepage control structures.

The results of the regression analysis were statistically significant, as shown by t tests on model regression coefficients. As

discussed, all of the HW/TW simple linear model predictor variables were significant at a level  $\alpha < 0.001$  (D.C. > 99.9%), with models for piezometers BU-2, DD-5, and ED-6 being exceptions. It has been previously hypothesized that BU-2 was placed in a "tight" zone, DD-5 has malfunctioned, and that ED-6 is above the normal phreatic surface. Results of t tests for the multiple linear models are confounded by multicorrelation, but provide some insights on the relative contribution of the two predictor variables to model performance. Though statistically significant, the overall success of the results can only be evaluated in relationship to intended applications. Implications of the results will be discussed in Section V.4.

Several techniques hold promise for the improvement of regression model performance. Possibilities for the refinement of the regression models include adding time as a predictor variable for piezometers showing time-increases and testing the effect of quadratic terms. Further research is needed to better describe antecedent headwater/tailwater time functions for comparison with piezometer data.

### V.3 Flow Net Analysis

Results of the flow net analysis indicate varying conditions in the five instrumented sections, and also indicate deviations from initially assumed conditions. While based on the recorded flow potentials, the flow net models represent a considerable idealization of the actual conditions. It is clear from the models, however, that the permeability

of the grouted zone is the critical factor controlling discharge through the foundation.

Flow net results seem to indicate a differential in the hydraulic conductivity of the foundation bedrock on either side of the grouted zone. The flow net models indicate a dissipation of energy upstream from the grouted zone that conforms with theory. However, the flow potential distribution on the downstream side of the grout curtain indicates conditions close to hydrostatic. For the condition of foundation bedrock isotropy, flow net symmetry would be expected. Widmann and Stauble obtained similar results from flow net modeling of heterogeneous metamorphic rock underlying the Schlegeis Arch Dam (59:208).

Several possible explanations exist with respect to the condition of foundation bedrock anisotropy shown by the flow net models. Since the principal dam axis is oriented roughly parallel to the strike of the bedrock and the strata dips approximately 40° SE, layered heterogeneity is a possible explanation for the apparent hydraulic conductivity differential. Though the dam is founded entirely on Unit 2 of the Sevier Shale, this unit grades into Unit 1 downstream of the project. As seen from the description of these units by TVA geologists (p. 15), Unit 1 is predominantly limestone, with less argillaceous material than Unit 2. Less material would be available to clog cavities and joint planes--this unit would therefore be more susceptible to the development of larger cavities.

Another possible contribution to the apparent hydraulic conductivity differential is the introduction of soil particulates from overlying

alluvial strata upstream of the grout curtain into bedrock conduits. This would not occur on the downstream bedrock-alluvium contact (as modeled) because of the flow direction.

Discharges calculated from the five flow net models are thought to provide a reasonable estimate of actual discharge quantities. Results for the five instrumented sections were fairly consistent (within an order of magnitude), owing to similar assumed geometry and material properties. As is the case with most seepage problems, the factor having the most impact on results is the assumed value of hydraulic conductivity. The total discharge estimate for foundation seepage (20 cfs) is considered reasonable in relation to the data analyzed and conditions at the project--however, it should only be considered an indication of the order of magnitude, owing to foundation heterogeneity.

The flow net analysis enhanced understanding and interpretation of regression analysis results by graphical depiction of piezometer location within the seepage field. The two methods of analysis should be considered complementary, since they are based on the same fundamental equations. As will be discussed in the following section, both analytical methods provide different types of information which are thought to be of use in monitoring for dam safety.

#### V.4 Implications

The research presented has implications for dam safety monitoring in general, in addition to implications regarding the Tellico project. Statistical analysis of monitored data is a relatively new application

that will require continuing evaluation as other project data are analyzed and presented.

An important potential application for the regression analysis presented is in the area of data validation and quality control. If lead project engineers confirm that recorded data for a given time period indicates safe conditions, then a legitimate objective is to detect possible deviations from these conditions. Each time the piezometers are observed, field personnel must determine if observed values are reasonable with respect to past behavior. The regression models would assist in this decision by providing an expected range of head (or pressure), given antecedent headwater/tailwater conditions.

Figure 32 illustrates the use of regression model results as a validation tool. Figure 32 is a "working graph," with model units converted to psi for initial interpretation of raw data. A possible application of this graph is use by field personnel to detect extreme or suspect values at the site in time to doublecheck the readings. The modeling also has the potential for systematic data validation checks, incorporable into computer algorithms. However, specifications associated with any procedures for the use of such should be approved by lead design engineers. Absolute magnitude should also be used as a validation criteria, based on a total design safety analysis. The purpose of the proposed validation checks is to improve data quality and detect data observations that differ significantly from past behavior. Immediate processing and evaluation is also a high priority.

# PIEZOMETER AD-2

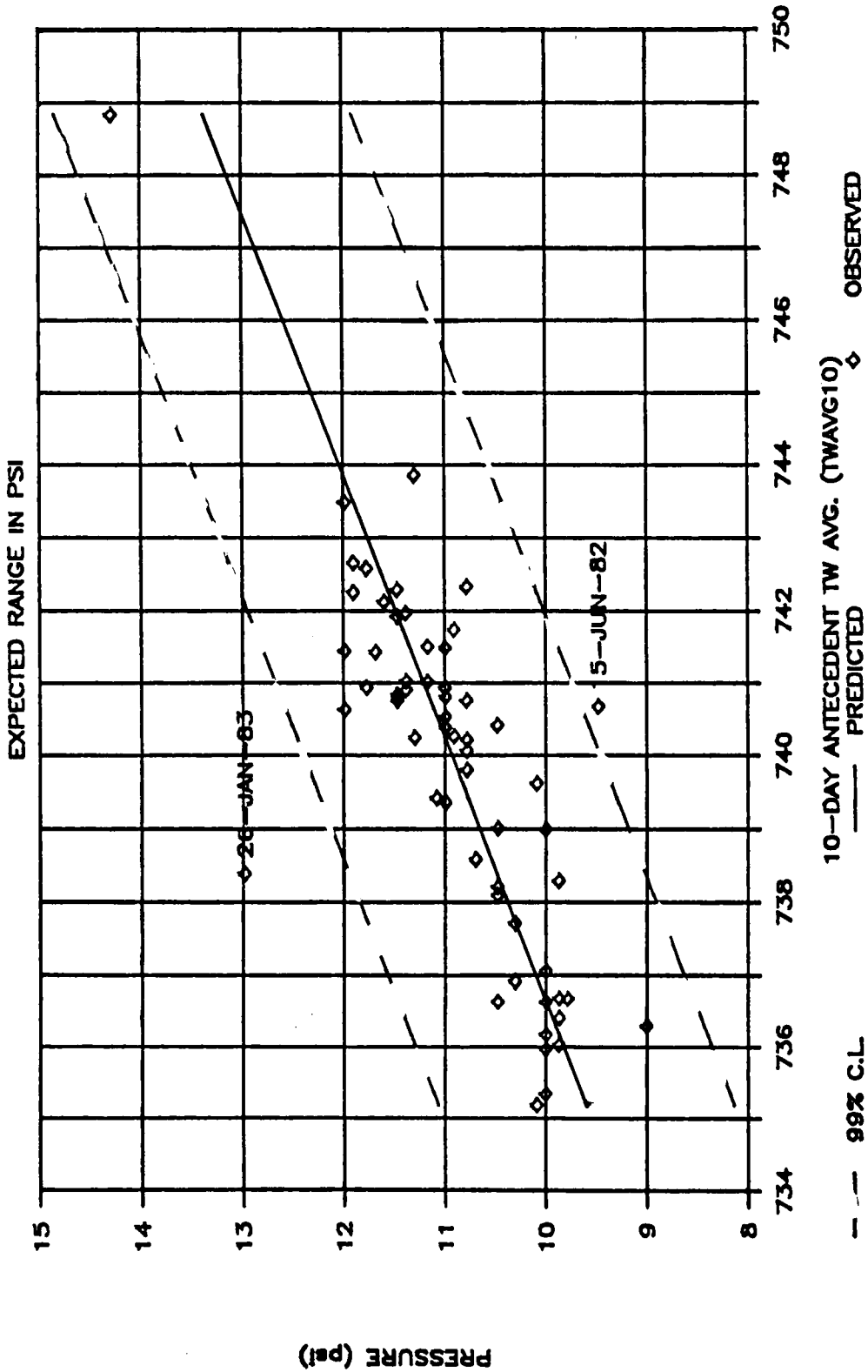


FIGURE 32. PLOT OF SIMPLE LINEAR REGRESSION MODEL EQUATION AND 99% CONFIDENCE LIMITS VS ANTECEDENT TAILWATER FOR PIEZOMETER AD-2

A second application for the modeling is comparative analysis of different samples. Comparison of results for the sample analyzed herein with a future sample could help identify changes in the seepage field with time. If little change in the seepage field has occurred, then statistical evidence should indicate that the two samples are from the same population. However, if change has occurred, the difference in regression parameter estimates for the two samples would deviate in excess of the respective parameter standard error of estimates. Further research is therefore necessary in order to realize the potential applications of the analysis presented herein.

The applicability of linear regression modeling of the type presented herein to other projects is uncertain. Similar model performance would be expected in similar conditions, in a fractured, jointed, and/or karstic strata. The modeling would be less effective in less permeable sections, because headwater/tailwater fluctuations would not be immediately transmitted to piezometers at depth. In this case, further research might identify an alternate method of dependent variable selection to improve model performance. Significant karst is found in many parts of the world, including the eastern U.S., Europe, central America, southeast Asia, and western Australia. There is potential, therefore, for applicability of linear regression modeling to other projects.

The modeling results have other specific implications for the Tellico project. The results indicate a significant reduction in flow potential by the grout curtain. Pressures close to hydrostatic are found under the downstream toe of the embankment, which is favorable

from the standpoint of stability. The estimated total seepage under the embankment (20 cfs) does not represent a significant figure in terms of economic water losses (0.35% of the estimated mean annual streamflow). However, the results obtained do not constitute complete evidence of total project safety. Other necessary components of dam safety evaluations include piping, stability, and earthquake analyses and on-site inspections. Continued monitoring is considered essential, because of the karstic nature of the foundation bedrock. As discussed in other research, changes in the geometry of seepage paths with time (i.e., cavitation and filling of conduits with particulates) can affect the distribution of pressures under a dam. Further conclusions regarding the implications of the results obtained to total project safety will be left to TVA design engineers.

The results obtained confirm that statistical methods, particularly regression, can be used to assist in analyzing monitoring data for dam safety. The regression model results were statistically significant and have possible applications in both initial validation and detailed evaluation of project data. Application of regression methods to monitoring represents a challenge to the engineer, who must select appropriate models and assess the significance of results. Support in the form of statistical and programming expertise is desirable, if not essential for implementation. If carefully planned and implemented, the methods presented can assist in monitoring for dam safety.

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## APPENDIX

### A.1 Sample Correlation Coefficient (r)

The sample correlation coefficient measures the degree of linear association between two variables. The sample correlation coefficient between two variables x and y is:

$$r_{xy} = \frac{\left[ \sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y}) \right]}{\left[ \sqrt{\sum_{i=1}^N (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^N (y_i - \bar{y})^2} \right]}. \quad (\text{A-1})$$

### A.2 General Derivation for Regression Parameters

The derivation of calculating formulae for parameter estimates are based on the use of calculus. Specifically, the objective is to minimize the sum of squared differences between observed and predicted values. Let G represent a function of the squared difference between observed and predicted values:

$$G = \sum_{i=1}^N (Y_i - Y_{h_i})^2, \quad (\text{A-2})$$

where

Y = observed Y value,

Y<sub>h</sub> = predicted Y value, and

$N$  = total number of  $i$  observations.

The estimation of a given parameter in Equ. A-2 is accomplished by substituting the appropriate regression equation, taking the derivative with respect to the parameter being estimated and setting this quantity to zero. For example, the condition specified for estimation of the regression coefficient  $b$  in A-2 may be stated as:

$$\frac{dG}{db} = 0 . \quad (A-3)$$

For the general case of  $k$  parameters, Equ. A-3 would be applied  $k$  times to produce a system of  $k$  linear equations with  $k$  unknowns. Younger (62) provides additional information on regression parameter estimates, calculating formulae, and computer routines.

### A.3 Coefficient of Determination (R-SQUARE)

An important statistic commonly used in describing overall model performance in regression analysis is the coefficient of determination. The sample coefficient of determination (R-SQUARE) is an estimate of the proportion of variation in the dependent variable  $Y$  which is explained by the model predictor variables. For both models, the coefficient of determination can be calculated as:

$$R\text{-SQUARE} = \frac{G}{\left[ \sum_{i=1}^N (Y_i - Y_m)^2 \right]} , \quad (A-4)$$

where

$Y_m$  = mean  $Y$ , and

$G$  = function in Equ. A-2.

For the simple linear model, the correlation coefficient ( $r$ ) and coefficient of determination (R-SQUARE) have the following relationship:

$$r = (\text{R-SQUARE})^{1/2} \text{ (simple linear model) .} \quad (\text{A-5})$$

For multiple regression, the computation of R-SQUARE is affected by multicollinearity and no simple calculating formula exists.

#### A.4 Standard Error of Estimate (S)

The standard error of estimate measures the average amount that observed  $Y$  values differ from predicted  $Y$  values. A general calculating formula for the standard error of estimate is:

$$S = \frac{\left[ \sum_{i=1}^N (y_i - y_h)^2 \right]}{DF} . \quad (\text{A-6})$$

where

DF = model degree of freedom.

The model degree of freedom (DF) is defined as:

$$DF = N - P , \quad (\text{A-7})$$

where

N = number of observations, and

P = number of parameters to be estimated.

#### A.5 The Normal Distribution

For any random variable, the normal distribution is a function of the sample mean  $Y_m$  and the population standard deviation  $s$ . According to Kleinbaum and Kupper (59:19), the normal distribution describes the behavior of the random variable  $Z$ , which is defined as:

$$Z = \frac{(N)^{1/2}(Y_m - u)}{s}, \quad (A-8)$$

where

$Y_m$  = sample mean,

$u$  = population mean,

$s$  = population standard deviation, and

$N$  = number of observations.

Use of the normal distribution is supported by the Central Limit Theorem. This theorem states that a collection of sample means ( $Y_m$ ) for different samples tends to be normally distributed about the population mean ( $u$ ) and that the variance of the  $Y_m$  values about  $u$  will not be as great as the variance of individual  $Y$  values (62:195).

### A.6 The t Distribution

According to Snedecor and Cochran (40:60), the t distribution describes the behavior of the random variable t, which is the deviation of the estimated mean  $Y_m$  from that of the population ( $u$ ) expressed as:

$$t = \frac{(N)^{1/2}(Y_m - u)}{S}, \quad (A-9)$$

where

$N$  = number of observations,

$Y_m$  = sample mean,

$u$  = population mean, and

$S$  = sample standard deviation.

According to Younger, the t distribution is a function of probability and model degree of freedom, and approaches the normal distribution as the degree of freedom approaches infinity (50:198).

### A.7 The Goodness of Fit Test

According to Younger, the goodness of fit test is often used to test the normality assumption (62:294). As described by Snedecor and Cochran (40:84), the test criterion is the CHI-SQUARE index:

$$\text{CHI-SQUARE} = \sum_{i=1}^k \frac{(f_i - F_i)}{F_i}, \quad (A-10)$$

where

$f_i$  = observed frequencies,

$F_i$  = expected normal frequencies, and

$k$  = number of classes used.

According to Snedecor and Cochran, if the data come from a normal distribution, this index follows a theoretical CHI-SQUARE distribution with  $(k-3)$  degrees of freedom (40:84). Test results are expressed as the significance level at which the hypothesis of normality can be rejected.

CHI-SQUARE indices were computed for multiple linear regression model error distribution using six classes of frequencies based on the number of standardized residuals from the mean. Table A-3 shows CHI-SQUARE indices for these data and a probability range within which the hypothesis of normality could be rejected. Test results indicate that, on the average, the hypothesis of normality for the individual model populations can be rejected at the 10-25% significance level (average CHI-SQUARE = 9.71).

#### A.8 t Test Statistics

The  $t$  statistic for testing the null hypothesis  $H_0: a = 0$  is:

$$t_a = \frac{A}{(S_a)}, \quad (A-11)$$

where

$S_a$  = standard error of the regression constant.

According to Younger, the standard error of the regression constant ( $S_a$ ) is an estimate of how much the value of  $A$  varies from sample to sample.

The  $t$  statistic for testing a null hypothesis for a given regression coefficient ( $B$ ) is:

$$t_b = \frac{B}{(S_b)} , \quad (A-12)$$

where

$S_b$  = standard error of the regression coefficient.

TABLE A-1. SUMMARY OF TVA PERMEABILITY DATA<sup>a</sup> FOR EMBANKMENT FOUNDATION

| BORING/<br>RANGE | STATION | DISTANCE <sup>b</sup><br>FROM C.L.<br>(ft) | SURFACE<br>ELEV.<br>(ft) | SOIL<br>TYPE | THICK-<br>NESS<br>(ft) | DEPTH<br>TO TOP<br>(ft) | PERMEABILITY<br>Kh<br>(cm/s) | Kv<br>(cm/s) |
|------------------|---------|--------------------------------------------|--------------------------|--------------|------------------------|-------------------------|------------------------------|--------------|
| A                | 6+50    | -                                          | -                        | -            | -                      | -                       | -                            | -            |
| US-29            | 7+40    | 0                                          | 757.1                    | SM           | 1.7                    | 17.0                    | 1.0E-4                       | 1.7E-5       |
| US-6             | 9+80.4  | 130 US                                     | 767.3                    | SM           | 1.1                    | 30.0                    | 5.8E-5                       | 2.3E-4       |
| B                | 10+35   | -                                          | -                        | -            | -                      | -                       | -                            | -            |
| US-7             | 15+80.4 | 130 US                                     | 755.8                    | ML           | 1.3                    | 20.2                    | 1.3E-5                       | 6.1E-5       |
| US-12            | 17+80.4 | 130 DS                                     | 755.5                    | ML           | 2.5                    | 5.0                     | 3.3E-5                       | 2.5E-5       |
|                  |         |                                            |                          | ML           | 2.5                    | 8.0                     | 1.8E-5                       | 1.3E-5       |
| C                | 20+85   | -                                          | -                        | -            | -                      | -                       | -                            | -            |
| US-8             | 21+80.4 | 130 US                                     | 762.0                    | CL           | 2.5                    | 18.0                    | 5.7E-5                       | 3.6E-6       |
| US-13            | 23+80.4 | 130 DS                                     | 763.2                    | ML           | 2.6                    | 8.0                     | 9.0E-7                       | 4.6E-7       |
|                  |         |                                            |                          | SM           | 2.6                    | 17.0                    | 5.2E-5                       | 1.0E-5       |
|                  |         |                                            |                          | SM           | 1.0                    | 24.5                    | 2.1E-4                       | 4.6E-4       |
| D                | 26+85   | -                                          | -                        | -            | -                      | -                       | -                            | -            |
| US-9             | 27+00   | 130 US                                     | 752.0                    | ML           | 2.5                    | 15.0                    | 3.2E-6                       | 2.6E-6       |
| US-14            | 28+00   | 130 DS                                     | 752.6                    | ML           | 2.5                    | 16.0                    | 5.4E-6                       | 3.3E-6       |
|                  |         |                                            |                          | SM           | 2.5                    | 19.0                    | 3.2E-5                       | 4.6E-6       |
| US-1             | 28+50   | 0                                          | 759.2                    | MH           | 2.0                    | 18.0                    | 4.4E-6                       | 4.8E-7       |
| E                | 30+50   | -                                          | -                        | -            | -                      | -                       | -                            | -            |
| US-2             | 30+50   | 0                                          | 794.6                    | SM           | 2.2                    | 8.0                     | 9.9E-5                       | 3.6E-6       |
| US-3             | 38+00   | 250 US                                     | 812.5                    | ML           | 2.5                    | 14.0                    | 2.0E-4                       | 2.2E-6       |
| US-4             | 42+50   | 700 US                                     | 816.7                    | SM           | 2.5                    | 14.0                    | 1.2E-5                       | 8.0E-6       |
|                  |         |                                            |                          | SM           | 2.0                    | 22.0                    | 1.4E-4                       | 5.6E-6       |

<sup>a</sup> Tennessee Valley Authority, Division of Construction, Construction Services Branch, Tellico Dam Project--Soil Investigation and Laboratory Testing," Report No. 50-7, 1968.

<sup>b</sup> Distance from centerline, US = upstream, DS = downstream.

TABLE A-2. DISTRIBUTION OF STANDARDIZED RESIDUALS FROM MULTIPLE LINEAR REGRESSION MODELS

| PIEZOMETER | PERCENT OF STANDARDIZED RESIDUALS WITHIN GIVEN RANGE <sup>a</sup> |       |       |       |       |       |      |      |
|------------|-------------------------------------------------------------------|-------|-------|-------|-------|-------|------|------|
|            | <-3                                                               | -3--2 | -2-1  | -1-0  | 0-1   | 1-2   | 2-3  | >3   |
| AU-1       | 0.00                                                              | 1.69  | 10.17 | 40.68 | 27.12 | 18.64 | 1.69 | 0.00 |
| AU-2       | 0.00                                                              | 5.08  | 8.47  | 25.42 | 49.15 | 10.17 | 1.69 | 0.00 |
| AU-3       | 0.00                                                              | 0.00  | 11.86 | 45.76 | 33.90 | 1.69  | 3.39 | 3.39 |
| AE         | 1.69                                                              | 0.00  | 5.08  | 42.37 | 37.29 | 13.56 | 0.00 | 0.00 |
| AD-1       | 0.00                                                              | 5.08  | 8.47  | 27.12 | 47.46 | 11.86 | 0.00 | 0.00 |
| AD-2       | 1.69                                                              | 0.00  | 3.39  | 47.46 | 40.68 | 5.08  | 0.00 | 1.69 |
| AD-3       | 0.00                                                              | 0.00  | 0.00  | 66.10 | 32.20 | 0.00  | 0.00 | 1.69 |
| AD-4       | 1.69                                                              | 0.00  | 1.69  | 40.68 | 49.15 | 5.08  | 1.69 | 0.00 |
| AD-5       | 0.00                                                              | 1.69  | 11.86 | 38.98 | 28.81 | 16.95 | 1.69 | 0.00 |
| AD-6       | 0.00                                                              | 1.72  | 15.52 | 32.76 | 34.48 | 12.07 | 3.45 | 0.00 |
| BU-1       | 1.69                                                              | 3.39  | 1.69  | 42.37 | 40.68 | 5.08  | 5.08 | 0.00 |
| BU-2       | 0.00                                                              | 0.00  | 15.25 | 38.98 | 23.73 | 18.64 | 3.39 | 0.00 |
| BU-3       | 0.00                                                              | 5.08  | 6.78  | 28.81 | 50.85 | 6.78  | 1.69 | 0.00 |
| BE         | 0.00                                                              | 3.39  | 11.86 | 35.59 | 28.81 | 20.34 | 0.00 | 0.00 |
| BD-1       | 0.00                                                              | 0.00  | 15.25 | 37.29 | 33.90 | 10.17 | 3.39 | 0.00 |
| BD-2       | 0.00                                                              | 0.00  | 8.47  | 45.76 | 42.37 | 1.69  | 0.00 | 1.69 |
| BD-3       | 0.00                                                              | 0.00  | 20.34 | 35.59 | 25.42 | 16.95 | 1.69 | 0.00 |
| BD-4       | 0.00                                                              | 1.69  | 3.39  | 55.93 | 30.51 | 3.39  | 0.00 | 5.08 |
| BD-5       | 0.00                                                              | 1.69  | 16.95 | 25.42 | 40.68 | 15.25 | 0.00 | 0.00 |
| BD-6       | 0.00                                                              | 1.69  | 16.95 | 33.90 | 32.20 | 11.86 | 3.39 | 0.00 |
| CU-1       | 0.00                                                              | 1.69  | 13.56 | 30.51 | 38.98 | 15.25 | 0.00 | 0.00 |
| CU-2       | 0.00                                                              | 3.39  | 10.17 | 38.98 | 33.90 | 11.86 | 0.00 | 1.69 |
| CU-3       | 0.00                                                              | 0.00  | 6.78  | 45.76 | 42.37 | 1.69  | 1.69 | 1.69 |
| CE         | 0.00                                                              | 3.39  | 8.47  | 37.29 | 47.46 | 1.69  | 0.00 | 1.69 |
| CD-1       | 0.00                                                              | 3.39  | 8.47  | 32.20 | 45.76 | 6.78  | 3.39 | 0.00 |
| CD-2       | 3.39                                                              | 1.69  | 5.08  | 25.42 | 57.63 | 6.78  | 0.00 | 0.00 |
| CD-3       | 0.00                                                              | 1.69  | 11.86 | 42.37 | 28.81 | 11.86 | 3.39 | 0.00 |
| CD-4       | 0.00                                                              | 1.69  | 11.86 | 38.98 | 38.98 | 1.69  | 6.78 | 0.00 |
| CD-5       | 1.69                                                              | 3.39  | 8.47  | 33.90 | 42.37 | 8.47  | 1.69 | 0.00 |
| CD-6       | 0.00                                                              | 0.00  | 18.64 | 37.29 | 32.20 | 8.47  | 1.69 | 1.69 |
| DU-1       | 0.00                                                              | 1.69  | 6.78  | 52.54 | 23.73 | 10.17 | 5.08 | 0.00 |
| DU-2       | 0.00                                                              | 1.69  | 15.25 | 18.64 | 55.93 | 6.78  | 1.69 | 0.00 |
| DD-1       | 0.00                                                              | 1.69  | 10.17 | 40.68 | 33.90 | 10.17 | 1.69 | 1.69 |
| DD-2       | 0.00                                                              | 1.69  | 15.25 | 28.81 | 37.29 | 15.25 | 1.69 | 0.00 |
| DD-4       | 0.00                                                              | 0.00  | 13.56 | 47.46 | 25.42 | 5.08  | 8.47 | 0.00 |
| DD-5       | 5.08                                                              | 0.00  | 5.08  | 18.64 | 71.19 | 0.00  | 0.00 | 0.00 |

TABLE A-2 (CONTINUED)

| PIEZOMETER | PERCENT OF STANDARDIZED RESIDUALS WITHIN GIVEN RANGE <sup>a</sup> |       |       |       |       |       |      |      |
|------------|-------------------------------------------------------------------|-------|-------|-------|-------|-------|------|------|
|            | <-3                                                               | -3--2 | -2-1  | -1-0  | 0-1   | 1-2   | 2-3  | >3   |
| EU-1       | 1.69                                                              | 3.39  | 10.17 | 22.03 | 55.93 | 6.78  | 0.00 | 0.00 |
| EU-2       | 1.69                                                              | 0.00  | 6.78  | 40.68 | 42.37 | 6.78  | 0.00 | 1.69 |
| EU-3       | 0.00                                                              | 0.00  | 15.52 | 32.76 | 41.38 | 6.90  | 1.72 | 1.72 |
| EE         | 0.00                                                              | 0.00  | 16.95 | 35.59 | 32.20 | 13.56 | 0.00 | 1.69 |
| ED-1       | 0.00                                                              | 0.00  | 15.25 | 40.68 | 23.73 | 18.64 | 1.69 | 0.00 |
| ED-2       | 0.00                                                              | 3.39  | 13.56 | 33.90 | 30.51 | 18.64 | 0.00 | 0.00 |
| ED-3       | 0.00                                                              | 0.00  | 16.95 | 37.29 | 25.42 | 18.64 | 1.69 | 0.00 |
| ED-4       | 1.69                                                              | 0.00  | 16.95 | 23.73 | 47.46 | 10.17 | 0.00 | 0.00 |
| ED-5       | 1.69                                                              | 0.00  | 3.39  | 40.68 | 50.85 | 3.39  | 0.00 | 0.00 |
| ED-6       | 0.00                                                              | 0.00  | 0.00  | 79.66 | 18.64 | 0.00  | 0.00 | 1.69 |
| H-1        | 0.00                                                              | 1.72  | 13.79 | 32.76 | 36.21 | 13.79 | 1.72 | 0.00 |
| H-2        | 0.00                                                              | 1.75  | 17.54 | 28.07 | 38.60 | 12.28 | 1.75 | 0.00 |
| H-3        | 0.00                                                              | 1.75  | 14.04 | 31.58 | 42.11 | 8.77  | 1.75 | 0.00 |
| H-4        | 0.00                                                              | 3.51  | 10.53 | 31.58 | 35.09 | 19.30 | 0.00 | 0.00 |
| H-5        | 1.79                                                              | 1.79  | 3.57  | 32.14 | 53.57 | 7.14  | 0.00 | 0.00 |
| H-6        | 1.72                                                              | 0.00  | 1.72  | 39.66 | 55.17 | 0.00  | 1.72 | 0.00 |
| H-7        | 1.72                                                              | 0.00  | 15.52 | 29.31 | 34.48 | 17.24 | 1.72 | 0.00 |
| H-8        | 0.00                                                              | 1.72  | 13.79 | 36.21 | 36.21 | 8.62  | 3.45 | 0.00 |
| H-8A       | 0.00                                                              | 3.45  | 8.62  | 37.93 | 39.66 | 6.90  | 3.45 | 0.00 |
| H-9        | 1.72                                                              | 3.45  | 1.72  | 44.83 | 39.66 | 5.17  | 3.45 | 0.00 |
| H-10       | 1.72                                                              | 1.72  | 0.00  | 46.55 | 37.93 | 10.34 | 1.72 | 0.00 |
| H-11       | 0.00                                                              | 3.45  | 10.34 | 36.21 | 36.21 | 10.34 | 3.45 | 0.00 |
| H-12       | 0.00                                                              | 5.17  | 3.45  | 41.38 | 37.93 | 8.62  | 3.45 | 0.00 |
| H-13       | 1.72                                                              | 3.45  | 3.45  | 41.38 | 37.93 | 10.34 | 1.72 | 0.00 |
| H-14       | 1.72                                                              | 1.72  | 5.17  | 41.38 | 36.21 | 10.34 | 3.45 | 0.00 |
| H-15       | 0.00                                                              | 3.45  | 10.34 | 36.21 | 36.21 | 10.34 | 3.45 | 0.00 |
| H-16       | 1.72                                                              | 1.72  | 6.90  | 36.21 | 43.10 | 6.90  | 3.45 | 0.00 |
| H-17       | 0.00                                                              | 1.72  | 12.07 | 37.93 | 32.76 | 12.07 | 3.45 | 0.00 |
| H-18       | 0.00                                                              | 1.72  | 1.72  | 55.17 | 31.03 | 5.17  | 1.72 | 3.45 |
| H-19       | 0.00                                                              | 0.00  | 8.62  | 44.83 | 36.21 | 6.90  | 0.00 | 3.45 |
| H-20       | 0.00                                                              | 3.45  | 6.90  | 41.38 | 34.48 | 10.34 | 1.72 | 1.72 |
| H-21       | 0.00                                                              | 0.00  | 15.52 | 43.10 | 24.14 | 12.07 | 5.17 | 0.00 |
| H-22       | 1.72                                                              | 0.00  | 1.72  | 53.45 | 34.48 | 5.17  | 1.72 | 1.72 |
| H-25       | 0.00                                                              | 3.33  | 3.33  | 53.33 | 23.33 | 13.33 | 3.33 | 0.00 |
| MEAN       | 0.57                                                              | 1.64  | 9.56  | 38.44 | 37.98 | 9.44  | 1.82 | 0.54 |
| STD NORMAL | 0.5                                                               | 2.0   | 13.5  | 32.0  | 32.0  | 13.5  | 2.0  | 0.5  |

<sup>a</sup> Percent of values falling within 1, 2, 3, and greater than 3 standard error of estimates of the value predicted by multiple regression.

TABLE A-3. CHI-SQUARE GOODNESS OF FIT TEST FOR NORMALITY APPLIED TO MULTIPLE LINEAR REGRESSION MODEL RESIDUALS

| PROBABILITY P<br>OF NORMAL<br>DISTRIBUTION <sup>a</sup> |            |               | PROBABILITY P<br>OF NORMAL<br>DISTRIBUTION <sup>a</sup> |            |               |
|---------------------------------------------------------|------------|---------------|---------------------------------------------------------|------------|---------------|
| PIEZOMETER                                              | CHI-SQUARE |               | PIEZOMETER                                              | CHI-SQUARE |               |
| AU-1                                                    | 4.05       | 0.750>P>0.500 | EU-1                                                    | 17.04      | P<0.005       |
| AU-2                                                    | 8.72       | 0.100>P>0.050 | EU-2                                                    | 7.6        | 0.250>P>0.100 |
| AU-3                                                    | 14.02      | P<0.005       | EU-3                                                    | 5.24       | 0.500>P>0.250 |
| AE                                                      | 7.39       | 0.250>P>0.100 | EE                                                      | 2.8        | 0.750>P>0.500 |
| AD-1                                                    | 8.43       | 0.100>P>0.050 | ED-1                                                    | 6.01       | 0.500>P>0.250 |
| AD-2                                                    | 13.51      | P<0.005       | ED-2                                                    | 3.06       | 0.750>P>0.500 |
| AD-3                                                    | 38.53      | P<0.005       | ED-3                                                    | 5.11       | 0.500>P>0.250 |
| AD-4                                                    | 16.1       | P<0.005       | ED-4                                                    | 8.57       | 0.100>P>0.050 |
| AD-5                                                    | 2.32       | 0.900>P>0.750 | ED-5                                                    | 18.36      | P<0.005       |
| AD-6                                                    | 0.69       | 0.950>P>0.900 | ED-6                                                    | 61.9       | P<0.005       |
| BU-1                                                    | 13.88      | P<0.005       | H-1                                                     | 0.88       | 0.950>P>0.900 |
| BU-2                                                    | 5.25       | 0.500>P>0.250 | H-2                                                     | 2.34       | 0.900>P>0.750 |
| BU-3                                                    | 11.5       | 0.010>P>0.005 | H-3                                                     | 3.18       | 0.750>P>0.500 |
| BE                                                      | 4.38       | 0.500>P>0.250 | H-4                                                     | 3.68       | 0.750>P>0.500 |
| BD-1                                                    | 2.87       | 0.750>P>0.500 | H-5                                                     | 15.16      | P<0.005       |
| BD-2                                                    | 14.26      | P<0.005       | H-6                                                     | 24.5       | P<0.005       |
| BD-3                                                    | 5.75       | 0.500>P>0.250 | H-7                                                     | 1.66       | 0.900>P>0.750 |
| BD-4                                                    | 20.16      | P<0.005       | H-8                                                     | 1.87       | 0.900>P>0.750 |
| BD-5                                                    | 4.88       | 0.500>P>0.250 | H-8A                                                    | 4.41       | 0.500>P>0.250 |
| BD-6                                                    | 1.04       | 0.950>P>0.900 | H-9                                                     | 13.51      | P<0.005       |
| CU-1                                                    | 3.07       | 0.750>P>0.500 | H-10                                                    | 12.66      | 0.010>P>0.005 |
| CU-2                                                    | 1.77       | 0.900>P>0.750 | H-11                                                    | 1.42       | 0.900>P>0.750 |
| CU-3                                                    | 14.83      | P<0.005       | H-12                                                    | 8.25       | 0.100>P>0.050 |
| CE                                                      | 12.04      | 0.010>P>0.005 | H-13                                                    | 7.93       | 0.100>P>0.050 |
| CD-1                                                    | 6.33       | 0.250>P>0.100 | H-14                                                    | 5.14       | 0.500>P>0.250 |
| CD-2                                                    | 20.06      | P<0.005       | H-15                                                    | 1.42       | 0.900>P>0.750 |
| CD-3                                                    | 2.61       | 0.750>P>0.500 | H-16                                                    | 6.08       | 0.500>P>0.250 |
| CD-4                                                    | 10.88      | 0.050>P>0.025 | H-17                                                    | 1.06       | 0.950>P>0.900 |
| CD-5                                                    | 5.2        | 0.500>P>0.250 | H-18                                                    | 19.38      | P<0.005       |
| CD-6                                                    | 4.48       | 0.500>P>0.250 | H-19                                                    | 7.63       | 0.250>P>0.100 |
| DU-1                                                    | 12.34      | 0.010>P>0.005 | H-20                                                    | 3.86       | 0.750>P>0.500 |
| DU-2                                                    | 16.23      | P<0.005       | H-21                                                    | 6.17       | 0.500>P>0.250 |
| DD-1                                                    | 2.58       | 0.750>P>0.500 | H-22                                                    | 17.19      | P<0.005       |
| DD-2                                                    | 1.6        | 0.900>P>0.750 | H-25                                                    | 7.1        | 0.250>P>0.100 |
| DD-4                                                    | 15.73      | P<0.005       |                                                         |            |               |
| DD-5                                                    | 44.34      | P<0.005       |                                                         |            |               |
|                                                         |            |               | Average = 9.71                                          |            |               |
|                                                         |            |               | (All Piezometers)                                       |            |               |
|                                                         |            |               | 0.25>P>0.100                                            |            |               |

<sup>a</sup>Probability that sample data comes from a normally-distributed population (degree of confidence D.C. is 100% times the probability P).

TABLE A-4. STANDARD ERROR OF ESTIMATE AND t TESTS FOR SIMPLE LINEAR REGRESSION MODEL PARAMETERS

| PIEZOMETER | HW/TW<br>VARIABLE<br>X | STD ERROR OF ESTIMATE<br>FOR MODEL PARAMETERS |                | t VALUES FOR $H_0$ :PARAMETER=0 AND D.C. in $H_1^a$ |        |                      |        | NO.<br>OF<br>OBS. |
|------------|------------------------|-----------------------------------------------|----------------|-----------------------------------------------------|--------|----------------------|--------|-------------------|
|            |                        | S <sub>a</sub>                                | S <sub>b</sub> | INTERCEPT (a)<br>t                                  | D.C.   | COEFFICIENT (b)<br>t | D.C.   |                   |
| AU-1       | HW10TO12               | 98.17                                         | 0.1211         | -1.4802                                             | 84.9%  | 9.5937               | >99.9% | 59                |
| AU-2       | HWAVG3                 | 67.11                                         | 0.0828         | -0.6552                                             | <50.0% | 12.6169              | >99.9% | 59                |
| AU-3       | HW                     | 44.29                                         | 0.0546         | -2.1351                                             | 96.1%  | 20.4224              | >99.9% | 59                |
| AE         | HWAVG30                | 99.98                                         | 0.1233         | 0.7894                                              | 56.5%  | 7.1558               | >99.9% | 59                |
| AD-1       | TWAVG3                 | 31.15                                         | 0.0421         | 10.4055                                             | >99.9% | 13.3865              | >99.9% | 59                |
| AD-2       | TWAVG10                | 49.05                                         | 0.0663         | 5.4451                                              | >99.9% | 9.6441               | >99.9% | 59                |
| AD-3       | TWAVG10                | 92.16                                         | 0.1246         | 2.7736                                              | 99.2%  | 5.2561               | >99.9% | 59                |
| AD-4       | TWAVG3                 | 41.86                                         | 0.0566         | 5.9448                                              | >99.9% | 11.7230              | >99.9% | 59                |
| AD-5       | TWAVG5                 | 27.52                                         | 0.0372         | 10.0775                                             | >99.9% | 16.7135              | >99.9% | 59                |
| AD-6       | TWAVG5                 | 27.64                                         | 0.0374         | 10.3930                                             | >99.9% | 16.3436              | >99.9% | 58                |
| BU-1       | HWAVG3                 | 72.64                                         | 0.0896         | 1.8571                                              | 92.8%  | 8.5836               | >99.9% | 59                |
| BU-2       | HWAVG30                | 119.49                                        | 0.1474         | 5.3147                                              | >99.9% | 1.2529               | 78.0%  | 59                |
| BU-3       | HW                     | 64.10                                         | 0.0790         | -0.0495                                             | <50.0% | 12.6560              | >99.9% | 59                |
| BE         | HW10TO12               | 55.47                                         | 0.0684         | 3.9365                                              | >99.9% | 10.3688              | >99.9% | 59                |
| BD-1       | TWAVG10                | 43.18                                         | 0.0584         | 4.9035                                              | >99.9% | 12.3274              | >99.9% | 59                |
| BD-2       | TWAVG5                 | 56.67                                         | 0.0766         | 5.7000                                              | >99.9% | 7.4298               | >99.9% | 59                |
| BD-3       | TWAVG10                | 28.04                                         | 0.0379         | 8.7008                                              | >99.9% | 17.6165              | >99.9% | 59                |
| BD-4       | TWAVG10                | 77.14                                         | 0.1043         | 1.6852                                              | 90.2%  | 7.9056               | >99.9% | 59                |
| BD-5       | TWAVG5                 | 25.42                                         | 0.0344         | 9.3872                                              | >99.9% | 19.7330              | >99.9% | 59                |
| BD-6       | TWAVG10                | 36.15                                         | 0.0489         | 7.9527                                              | >99.9% | 12.4987              | >99.9% | 59                |
| CU-1       | HW                     | 73.53                                         | 0.0907         | -1.3544                                             | 81.5%  | 12.3210              | >99.9% | 59                |
| CU-2       | HW                     | 80.08                                         | 0.0987         | -1.4075                                             | 82.9%  | 11.4824              | >99.9% | 59                |
| CU-3       | TW10TO12               | 95.49                                         | 0.1291         | 1.4089                                              | 83.0%  | 7.0652               | >99.9% | 59                |
| CE         | TW10TO12               | 96.28                                         | 0.1302         | 3.5283                                              | >99.9% | 4.7225               | >99.9% | 59                |
| CD-1       | TWAVG30                | 52.18                                         | 0.0705         | 2.1133                                              | 95.9%  | 12.0837              | >99.9% | 59                |
| CD-2       | TWAVG3                 | 48.72                                         | 0.0659         | 3.6427                                              | >99.9% | 11.5505              | >99.9% | 59                |
| CD-3       | TWAVG3                 | 21.27                                         | 0.0287         | 11.7416                                             | >99.9% | 23.0967              | >99.9% | 59                |
| CD-4       | TWAVG3                 | 31.20                                         | 0.0422         | 6.5793                                              | >99.9% | 17.1286              | >99.9% | 59                |
| CD-5       | TWAVG5                 | 38.33                                         | 0.0518         | 4.4686                                              | >99.9% | 14.7872              | >99.9% | 59                |
| CD-6       | TWAVG10                | 27.51                                         | 0.0372         | 3.0975                                              | 99.6%  | 23.7700              | >99.9% | 59                |
| DU-1       | HW                     | 73.47                                         | 0.0906         | -1.4184                                             | 83.2%  | 12.3197              | >99.9% | 59                |
| DU-2       | HW                     | 110.96                                        | 0.1368         | -0.5135                                             | <50.0% | 7.7719               | >99.9% | 59                |
| DD-1       | TWAVG3                 | 34.77                                         | 0.0470         | 6.2326                                              | >99.9% | 15.0634              | >99.9% | 59                |
| DD-2       | TWAVG3                 | 25.48                                         | 0.0344         | 7.8613                                              | >99.9% | 21.1429              | >99.9% | 59                |
| DD-4       | TWAVG5                 | 42.57                                         | 0.0575         | 4.4708                                              | >99.9% | 12.8658              | >99.9% | 59                |
| DD-5       | TWAVG10                | 235.42                                        | 0.3182         | -0.0019                                             | <50.0% | 3.1235               | 99.6%  | 59                |

TABLE A-4 (CONTINUED)

| PIEZOMETER | HW/TW<br>VARIABLE | STD ERROR OF ESTIMATE<br>FOR MODEL PARAMETERS |        | t VALUES FOR Ho:PARAMETER=0 AND D.C. IN H1 <sup>a</sup><br>INTERCEPT |        |         |        | NO.<br>OF<br>OBS. |
|------------|-------------------|-----------------------------------------------|--------|----------------------------------------------------------------------|--------|---------|--------|-------------------|
|            | X                 | Sa                                            | Sb     | t                                                                    | D.C.   | t       | D.C.   |                   |
| EU-1       | HW                | 181.58                                        | 0.2239 | 0.4977                                                               | <50.0% | 3.9423  | >99.9% | 59                |
| EU-2       | HWAVG3            | 43.15                                         | 0.0532 | -0.2709                                                              | <50.0% | 19.0137 | >99.9% | 59                |
| EU-3       | HW                | 33.07                                         | 0.0408 | -1.1708                                                              | 74.4%  | 25.6562 | >99.9% | 58                |
| EE         | HWAVG3            | 39.11                                         | 0.0482 | 8.2977                                                               | >99.9% | 12.0207 | >99.9% | 59                |
| ED-1       | TWAVG10           | 39.22                                         | 0.0530 | 3.2646                                                               | 99.8%  | 15.7143 | >99.9% | 59                |
| ED-2       | HW                | 61.57                                         | 0.0759 | 3.3963                                                               | 99.8%  | 9.3779  | >99.9% | 59                |
| ED-3       | HWAVG3            | 68.22                                         | 0.0841 | 4.5402                                                               | >99.9% | 7.0403  | >99.9% | 59                |
| ED-4       | TWAVG3            | 59.76                                         | 0.0808 | 6.8900                                                               | >99.9% | 5.5097  | >99.9% | 59                |
| ED-5       | TW4TO6            | 90.73                                         | 0.1226 | 1.3172                                                               | 80.5%  | 6.8632  | >99.9% | 59                |
| ED-6       | TWAVG30           | 18.72                                         | 0.0253 | 40.8037                                                              | >99.9% | 0.8435  | 59.7%  | 59                |
| H-1        | TWAVG5            | 17.40                                         | 0.0235 | 15.2931                                                              | >99.9% | 27.3157 | >99.9% | 58                |
| H-2        | TWAVG5            | 17.54                                         | 0.0237 | 16.8084                                                              | >99.9% | 25.4631 | >99.9% | 57                |
| H-3        | TWAVG10           | 22.22                                         | 0.0300 | 12.6370                                                              | >99.9% | 20.7256 | >99.9% | 57                |
| H-4        | TWAVG10           | 20.71                                         | 0.0280 | 13.5745                                                              | >99.9% | 22.2217 | >99.9% | 57                |
| H-5        | TWAVG10           | 30.66                                         | 0.0414 | 8.8273                                                               | >99.9% | 15.3448 | >99.9% | 56                |
| H-6        | TWAVG10           | 32.92                                         | 0.0445 | 7.4653                                                               | >99.9% | 15.0533 | >99.9% | 58                |
| H-7        | TWAVG10           | 17.05                                         | 0.0230 | 18.1727                                                              | >99.9% | 25.3094 | >99.9% | 58                |
| H-8        | TWAVG5            | 16.36                                         | 0.0221 | 12.6353                                                              | >99.9% | 32.6645 | >99.9% | 58                |
| H-8A       | TWAVG5            | 15.88                                         | 0.0215 | 13.6324                                                              | >99.9% | 33.0308 | >99.9% | 58                |
| H-9        | TWAVG5            | 19.58                                         | 0.0265 | 10.1358                                                              | >99.9% | 27.6964 | >99.9% | 58                |
| H-10       | TWAVG5            | 17.99                                         | 0.0243 | 10.7676                                                              | >99.9% | 30.4221 | >99.9% | 58                |
| H-11       | TWAVG5            | 15.93                                         | 0.0215 | 12.6556                                                              | >99.9% | 33.8547 | >99.9% | 58                |
| H-12       | TWAVG5            | 16.27                                         | 0.0220 | 12.1975                                                              | >99.9% | 33.3346 | >99.9% | 58                |
| H-13       | TWAVG5            | 18.72                                         | 0.0253 | 10.4205                                                              | >99.9% | 29.1589 | >99.9% | 58                |
| H-14       | TWAVG5            | 18.47                                         | 0.0250 | 9.6243                                                               | >99.9% | 30.4891 | >99.9% | 58                |
| H-15       | TWAVG5            | 16.95                                         | 0.0229 | 11.1216                                                              | >99.9% | 32.5966 | >99.9% | 58                |
| H-16       | TWAVG3            | 20.76                                         | 0.0281 | 9.7814                                                               | >99.9% | 25.9178 | >99.9% | 58                |
| H-17       | TWAVG5            | 17.28                                         | 0.0234 | 11.2378                                                              | >99.9% | 31.6530 | >99.9% | 58                |
| H-18       | TWAVG5            | 23.49                                         | 0.0318 | 9.1940                                                               | >99.9% | 22.3546 | >99.9% | 58                |
| H-19       | TWAVG5            | 22.38                                         | 0.0303 | 8.4061                                                               | >99.9% | 24.7131 | >99.9% | 58                |
| H-20       | TWAVG5            | 20.04                                         | 0.0271 | 10.2236                                                              | >99.9% | 26.7761 | >99.9% | 58                |
| H-21       | TWAVG5            | 19.55                                         | 0.0264 | 9.6804                                                               | >99.9% | 28.2716 | >99.9% | 58                |
| H-22       | TW4TO6            | 59.87                                         | 0.0809 | 2.6521                                                               | 98.9%  | 9.8094  | >99.9% | 58                |
| H-25       | TW4TO6            | 63.18                                         | 0.0854 | 2.9362                                                               | 99.3%  | 8.9031  | >99.9% | 30                |

<sup>a</sup>t for  $H_0$ :Parameter = 0 and the degree of confidence that  $H_1$ :Parameter = 0 is true (see definition of hypothesis, p. ).

TABLE A-5. STANDARD ERROR OF ESTIMATE FOR MULTIPLE LINEAR REGRESSION MODEL PARAMETERS

| PIEZOMETER | HEADWATER<br>VARIABLE | TAILWATER<br>VARIABLE | STANDARD ERROR OF ESTIMATE<br>FOR MODEL PARAMETERS |        |        | NO.<br>OF<br>OBS. |
|------------|-----------------------|-----------------------|----------------------------------------------------|--------|--------|-------------------|
|            | X1                    | X2                    | Sa                                                 | Sb1    | Sb2    |                   |
| AU-1       | HW10T012              | TWAVG30               | 103.70                                             | 0.1672 | 0.1668 | 59                |
| AU-2       | HWAVG3                | TWAVG10               | 66.97                                              | 0.1084 | 0.0968 | 59                |
| AU-3       | HW                    | TWAVG30               | 47.58                                              | 0.0745 | 0.0772 | 59                |
| AE         | HWAVG30               | TWAVG30               | 99.11                                              | 0.1648 | 0.1577 | 59                |
| AD-1       | HWAVG3                | TWAVG3                | 41.78                                              | 0.0680 | 0.0468 | 59                |
| AD-2       | HWAVG3                | TWAVG10               | 60.54                                              | 0.0980 | 0.0875 | 59                |
| AD-3       | HWAVG3                | TWAVG10               | 116.37                                             | 0.1884 | 0.1683 | 59                |
| AD-4       | HWAVG3                | TWAVG3                | 58.11                                              | 0.0946 | 0.0650 | 59                |
| AD-5       | HWAVG3                | TWAVG5                | 34.26                                              | 0.0557 | 0.0407 | 59                |
| AD-6       | HWAVG3                | TWAVG5                | 33.65                                              | 0.0547 | 0.0399 | 58                |
|            |                       |                       |                                                    |        |        |                   |
| BU-1       | HWAVG3                | TWAVG5                | 68.14                                              | 0.1109 | 0.0809 | 59                |
| BU-2       | HWAVG30               | TW10T012              | 121.11                                             | 0.1793 | 0.1692 | 59                |
| BU-3       | HW                    | TWAVG30               | 68.73                                              | 0.1077 | 0.1115 | 59                |
| BE         | HW10T012              | TWAVG30               | 57.50                                              | 0.0927 | 0.0925 | 59                |
| BD-1       | HWAVG3                | TWAVG10               | 44.61                                              | 0.0722 | 0.0645 | 59                |
| BD-2       | HWAVG10               | TWAVG5                | 84.61                                              | 0.1342 | 0.0954 | 59                |
| BD-3       | HWAVG3                | TWAVG10               | 26.48                                              | 0.0429 | 0.0383 | 59                |
| BD-4       | HWAVG3                | TWAVG10               | 93.68                                              | 0.1517 | 0.1354 | 59                |
| BD-5       | HWAVG3                | TWAVG5                | 29.67                                              | 0.0483 | 0.0352 | 59                |
| BD-6       | HWAVG3                | TWAVG10               | 35.79                                              | 0.0579 | 0.0517 | 59                |
|            |                       |                       |                                                    |        |        |                   |
| CU-1       | HW                    | TWAVG30               | 77.76                                              | 0.1218 | 0.1261 | 59                |
| CU-2       | HW                    | TWAVG30               | 84.19                                              | 0.1319 | 0.1366 | 59                |
| CU-3       | HW10T012              | TW10T012              | 102.38                                             | 0.1541 | 0.1515 | 59                |
| CE         | HWAVG30               | TW10T012              | 118.45                                             | 0.1754 | 0.1655 | 59                |
| CD-1       | HWAVG10               | TWAVG30               | 52.47                                              | 0.0848 | 0.0860 | 59                |
| CD-2       | HWAVG3                | TWAVG3                | 75.01                                              | 0.1222 | 0.0840 | 59                |
| CD-3       | HWAVG3                | TWAVG3                | 31.64                                              | 0.0515 | 0.0354 | 59                |
| CD-4       | HWAVG3                | TWAVG3                | 44.88                                              | 0.0731 | 0.0502 | 59                |
| CD-5       | HWAVG3                | TWAVG5                | 48.49                                              | 0.0789 | 0.0576 | 59                |
| CD-6       | HWAVG3                | TWAVG10               | 29.28                                              | 0.0474 | 0.0423 | 59                |
|            |                       |                       |                                                    |        |        |                   |
| DU-1       | HW                    | TWAVG30               | 78.82                                              | 0.1235 | 0.1279 | 59                |
| DU-2       | HW                    | TWAVG3                | 111.90                                             | 0.1777 | 0.1216 | 59                |
| DD-1       | HWAVG3                | TWAVG3                | 48.78                                              | 0.0794 | 0.0546 | 59                |
| DD-2       | HWAVG3                | TWAVG3                | 36.65                                              | 0.0597 | 0.0410 | 59                |
| DD-4       | HWAVG3                | TWAVG5                | 58.45                                              | 0.0951 | 0.0694 | 59                |
| DD-5       | HW10T012              | TWAVG10               | 305.08                                             | 0.4662 | 0.3993 | 59                |

TABLE A-5 (CONTINUED)

| PIEZOMETER | HEADWATER      | TAILWATER      | STANDARD ERROR OF ESTIMATE |                   |                   | NO.<br>OF<br>OBS. |
|------------|----------------|----------------|----------------------------|-------------------|-------------------|-------------------|
|            | VARIABLE<br>X1 | VARIABLE<br>X2 | FOR MODEL<br>Sa            | PARAMETERS<br>Sb1 | PARAMETERS<br>Sb2 |                   |
| EU-1       | HW             | TWAVG30        | 195.01                     | 0.3055            | 0.3163            | 59                |
| EU-2       | HWAVG3         | TWAVG30        | 46.25                      | 0.0736            | 0.0765            | 59                |
| EU-3       | HW             | TWAVG30        | 35.62                      | 0.0557            | 0.0578            | 58                |
| EE         | HWAVG3         | TWAVG30        | 41.94                      | 0.0667            | 0.0694            | 59                |
| ED-1       | HWAVG3         | TWAVG10        | 46.23                      | 0.0748            | 0.0668            | 59                |
| ED-2       | HW             | TWAVG30        | 65.91                      | 0.1033            | 0.1069            | 59                |
| ED-3       | HWAVG3         | TWAVG30        | 71.88                      | 0.1144            | 0.1189            | 59                |
| ED-4       | HWAVG5         | TWAVG3         | 97.08                      | 0.1573            | 0.1067            | 59                |
| ED-5       | HWAVG3         | TW4TO6         | 118.66                     | 0.1855            | 0.1590            | 59                |
| ED-6       | HW4TO6         | TWAVG30        | 21.62                      | 0.0341            | 0.0344            | 59                |
| H-1        | HWAVG3         | TWAVG5         | 21.87                      | 0.0356            | 0.0259            | 58                |
| H-2        | HWAVG3         | TWAVG5         | 19.72                      | 0.0321            | 0.0233            | 57                |
| H-3        | HWAVG3         | TWAVG10        | 20.32                      | 0.0328            | 0.0292            | 57                |
| H-4        | HWAVG3         | TWAVG10        | 19.65                      | 0.0318            | 0.0283            | 57                |
| H-5        | HWAVG3         | TWAVG10        | 32.17                      | 0.0521            | 0.0461            | 56                |
| H-6        | HWAVG3         | TWAVG10        | 39.66                      | 0.0642            | 0.0572            | 58                |
| H-7        | HWAVG3         | TWAVG10        | 18.69                      | 0.0303            | 0.0270            | 58                |
| H-8        | HWAVG3         | TWAVG5         | 21.57                      | 0.0351            | 0.0255            | 58                |
| H-8A       | HWAVG3         | TWAVG5         | 20.59                      | 0.0335            | 0.0244            | 58                |
| H-9        | HWAVG3         | TWAVG5         | 27.81                      | 0.0452            | 0.0329            | 58                |
| H-10       | HWAVG3         | TWAVG5         | 25.05                      | 0.0408            | 0.0296            | 58                |
| H-11       | HWAVG3         | TWAVG5         | 21.18                      | 0.0345            | 0.0251            | 58                |
| H-12       | HWAVG3         | TWAVG5         | 22.07                      | 0.0359            | 0.0261            | 58                |
| H-13       | HWAVG3         | TWAVG5         | 27.02                      | 0.0440            | 0.0320            | 58                |
| H-14       | HWAVG3         | TWAVG5         | 27.66                      | 0.0450            | 0.0327            | 58                |
| H-15       | HWAVG3         | TWAVG5         | 23.31                      | 0.0379            | 0.0276            | 58                |
| H-16       | HWAVG3         | TWAVG3         | 31.06                      | 0.0506            | 0.0346            | 58                |
| H-17       | HWAVG3         | TWAVG5         | 24.12                      | 0.0392            | 0.0285            | 58                |
| H-18       | HWAVG3         | TWAVG5         | 35.08                      | 0.0571            | 0.0415            | 58                |
| H-19       | HWAVG3         | TWAVG5         | 32.04                      | 0.0521            | 0.0379            | 58                |
| H-20       | HWAVG3         | TWAVG5         | 29.09                      | 0.0473            | 0.0344            | 58                |
| H-21       | HWAVG3         | TWAVG5         | 28.68                      | 0.0467            | 0.0339            | 58                |
| H-22       | HWAVG3         | TW4TO6         | 78.32                      | 0.1225            | 0.1047            | 58                |
| H-25       | HWAVG3         | TW4TO6         | 88.62                      | 0.1408            | 0.1106            | 30                |

TABLE A-6. t TESTS FOR MULTIPLE LINEAR REGRESSION MODEL PARAMETERS

| PIEZOMETER | HEADWATER | TAILWATER | t VALUES FOR Ho:PARAMETER=0 AND D.C. in H1 <sup>a</sup> |        |                  |        |                  |        | NO.<br>OF<br>OBS. |
|------------|-----------|-----------|---------------------------------------------------------|--------|------------------|--------|------------------|--------|-------------------|
|            | VARIABLE  | VARIABLE  | INTERCEPT (A)                                           |        | COEFFICIENT (b1) |        | COEFFICIENT (b2) |        |                   |
|            | X1        | X2        | t                                                       | D.C.   | t                | D.C.   | t                | D.C.   |                   |
| AU-1       | HW10TO12  | TWAVG30   | -1.3738                                                 | 82.0%  | 7.0085           | >99.9% | -0.0927          | <50.0% | 59                |
| AU-2       | HWAVG3    | TWAVG10   | -1.0271                                                 | 68.0%  | 8.3794           | >99.9% | 1.8827           | 93.2%  | 59                |
| AU-3       | HW        | TWAVG30   | -1.9427                                                 | 94.1%  | 15.0497          | >99.9% | -0.1293          | <50.0% | 59                |
| AE         | HWAVG30   | TWAVG30   | 0.2264                                                  | <50.0% | 3.7113           | >99.9% | 2.3646           | 97.8%  | 59                |
| AD-1       | HWAVG3    | TWAVG3    | 3.8831                                                  | >99.9% | 4.9721           | >99.9% | 8.8047           | >99.9% | 59                |
| AD-2       | HWAVG3    | TWAVG10   | 3.4360                                                  | >99.9% | 1.6230           | 88.7%  | 6.2262           | >99.9% | 59                |
| AD-3       | HWAVG3    | TWAVG10   | 2.1516                                                  | 96.2%  | 0.0747           | <50.0% | 3.8416           | >99.9% | 59                |
| AD-4       | HWAVG3    | TWAVG3    | 0.8539                                                  | 60.2%  | 4.3990           | >99.9% | 7.3240           | >99.9% | 59                |
| AD-5       | HWAVG3    | TWAVG5    | 4.2140                                                  | >99.9% | 5.1996           | >99.9% | 11.8979          | >99.9% | 59                |
| AD-6       | HWAVG3    | TWAVG5    | 4.4270                                                  | >99.9% | 5.4514           | >99.9% | 11.7837          | >99.9% | 58                |
| BU-1       | HWAVG3    | TWAVG5    | 1.9276                                                  | 93.9%  | 5.0022           | >99.9% | 2.9646           | 99.5%  | 59                |
| BU-2       | HWAVG30   | TW10TO12  | 5.9263                                                  | >99.9% | 2.4011           | 97.9%  | -2.2549          | 97.1%  | 59                |
| BU-3       | HW        | TWAVG30   | -0.2189                                                 | <50.0% | 8.9539           | >99.9% | 0.5018           | <50.0% | 59                |
| BE         | HW10TO12  | TWAVG30   | 3.3625                                                  | 99.8%  | 6.6476           | >99.9% | 1.4647           | 84.5%  | 59                |
| BD-1       | HWAVG3    | TWAVG10   | 1.5830                                                  | 87.6%  | 5.2596           | >99.9% | 7.6571           | >99.9% | 59                |
| BD-2       | HWAVG10   | TWAVG5    | 2.1493                                                  | 96.2%  | 2.1919           | 96.6%  | 4.5827           | >99.9% | 59                |
| BD-3       | HWAVG3    | TWAVG10   | 5.2180                                                  | >99.9% | 6.6445           | >99.9% | 13.0220          | >99.9% | 59                |
| BD-4       | HWAVG3    | TWAVG10   | 0.1039                                                  | <50.0% | 2.1346           | 96.1%  | 4.6666           | >99.9% | 59                |
| BD-5       | HWAVG3    | TWAVG5    | 3.4134                                                  | >99.9% | 6.2030           | >99.9% | 15.2091          | >99.9% | 59                |
| BD-6       | HWAVG3    | TWAVG10   | 4.4692                                                  | >99.9% | 5.9267           | >99.9% | 7.8621           | >99.9% | 59                |
| CU-1       | HW        | TWAVG30   | -1.7450                                                 | 91.1%  | 8.2625           | >99.9% | 1.3488           | 81.4%  | 59                |
| CU-2       | HW        | TWAVG30   | -1.8832                                                 | 93.2%  | 7.5318           | >99.9% | 1.5814           | 87.6%  | 59                |
| CU-3       | HW10TO12  | TW10TO12  | -0.5846                                                 | <50.0% | 3.5880           | >99.9% | 3.7561           | >99.9% | 59                |
| CE         | HWAVG30   | TW10TO12  | 2.8328                                                  | 99.3%  | 0.0617           | <50.0% | 3.6780           | >99.9% | 59                |
| CD-1       | HWAVG10   | TWAVG30   | 0.1408                                                  | <50.0% | 4.1134           | >99.9% | 7.0823           | >99.9% | 59                |
| CD-2       | HWAVG3    | TWAVG3    | 0.5805                                                  | <50.0% | 2.2906           | 97.4%  | 7.5630           | >99.9% | 59                |
| CD-3       | HWAVG3    | TWAVG3    | 5.4766                                                  | >99.9% | 3.0998           | 99.6%  | 16.7251          | >99.9% | 59                |
| CD-4       | HWAVG3    | TWAVG3    | 1.6375                                                  | 89.1%  | 3.7687           | >99.9% | 11.9212          | >99.9% | 59                |
| CD-5       | HWAVG3    | TWAVG5    | -0.1554                                                 | <50.0% | 4.9408           | >99.9% | 10.0890          | >99.9% | 59                |
| CD-6       | HWAVG3    | TWAVG10   | 0.0350                                                  | <50.0% | 4.7818           | >99.9% | 17.7028          | >99.9% | 59                |
| DU-1       | HW        | TWAVG30   | -1.1759                                                 | 74.6%  | 9.3255           | >99.9% | -0.4248          | <50.0% | 59                |
| DU-2       | HW        | TWAVG3    | -0.5076                                                 | <50.0% | 5.8552           | >99.9% | 0.2063           | <50.0% | 59                |
| DD-1       | HWAVG3    | TWAVG3    | 1.1576                                                  | 73.8%  | 4.2142           | >99.9% | 10.2120          | >99.9% | 59                |
| DD-2       | HWAVG3    | TWAVG3    | 2.5304                                                  | 98.4%  | 3.7655           | >99.9% | 15.2915          | >99.9% | 59                |
| DD-4       | HWAVG3    | TWAVG5    | 0.6431                                                  | <50.0% | 3.5006           | >99.9% | 8.3874           | >99.9% | 59                |
| DD-5       | HW10TO12  | TWAVG10   | -0.9283                                                 | 63.5%  | 1.4379           | 83.7%  | 1.6065           | 88.2%  | 59                |

TABLE A-6 (CONTINUED)

| PIEZOMETER | HEADWATER | TAILWATER | t VALUES FOR Ho:PARAMETER=0 AND D.C. in H1 <sup>a</sup> |        |                  |        |                  |        | NO.<br>OF<br>OBS. |
|------------|-----------|-----------|---------------------------------------------------------|--------|------------------|--------|------------------|--------|-------------------|
|            | VARIABLE  | VARIABLE  | INTERCEPT (A)                                           |        | COEFFICIENT (b1) |        | COEFFICIENT (b2) |        |                   |
|            | X1        | X2        | t                                                       | D.C.   | t                | D.C.   | t                | D.C.   |                   |
| EU-1       | HW        | TWAVG30   | 0.3785                                                  | <50.0% | 2.7233           | 99.1%  | 0.2467           | <50.0% | 59                |
| EU-2       | HWAVG3    | TWAVG30   | -0.1359                                                 | <50.0% | 13.9848          | >99.9% | -0.3432          | <50.0% | 59                |
| EU-3       | HW        | TWAVG30   | -1.1103                                                 | 71.7%  | 18.7477          | >99.9% | 0.0664           | <50.0% | 58                |
| EE         | HWAVG3    | TWAVG30   | 7.6487                                                  | >99.9% | 8.5098           | >99.9% | 0.2617           | <50.0% | 59                |
| ED-1       | HWAVG3    | TWAVG10   | 1.0396                                                  | 68.5%  | 2.8766           | 99.4%  | 10.5503          | >99.9% | 59                |
| ED-2       | HW        | TWAVG30   | 2.9490                                                  | 99.5%  | 6.4582           | >99.9% | 0.6492           | <50.0% | 59                |
| ED-3       | HWAVG3    | TWAVG30   | 3.8178                                                  | >99.9% | 4.1914           | >99.9% | 1.4432           | 83.9%  | 59                |
| ED-4       | HWAVG5    | TWAVG3    | 3.7117                                                  | >99.9% | 0.6736           | <50.0% | 3.7316           | >99.9% | 59                |
| ED-5       | HWAVG3    | TW4TO6    | 0.5354                                                  | <50.0% | 0.7364           | 53.4%  | 4.8277           | >99.9% | 59                |
| ED-6       | HW4TO6    | TWAVG30   | 35.2327                                                 | >99.9% | 0.2088           | <50.0% | 0.4793           | <50.0% | 59                |
| H-1        | HWAVG3    | TWAVG5    | 8.3862                                                  | >99.9% | 5.0482           | >99.9% | 21.5391          | >99.9% | 58                |
| H-2        | HWAVG3    | TWAVG5    | 9.9139                                                  | >99.9% | 6.6355           | >99.9% | 21.6619          | >99.9% | 57                |
| H-3        | HWAVG3    | TWAVG10   | 9.5130                                                  | >99.9% | 6.9931           | >99.9% | 16.7431          | >99.9% | 57                |
| H-4        | HWAVG3    | TWAVG10   | 10.3306                                                 | >99.9% | 6.4558           | >99.9% | 17.8037          | >99.9% | 57                |
| H-5        | HWAVG3    | TWAVG10   | 5.3301                                                  | >99.9% | 4.9747           | >99.9% | 10.5569          | >99.9% | 56                |
| H-6        | HWAVG3    | TWAVG10   | 4.7532                                                  | >99.9% | 2.3860           | 97.8%  | 10.1239          | >99.9% | 58                |
| H-7        | HWAVG3    | TWAVG10   | 13.9939                                                 | >99.9% | 4.2779           | >99.9% | 18.7991          | >99.9% | 58                |
| H-8        | HWAVG3    | TWAVG5    | 6.3923                                                  | >99.9% | 4.2600           | >99.9% | 25.5268          | >99.9% | 58                |
| H-8A       | HWAVG3    | TWAVG5    | 7.1115                                                  | >99.9% | 4.5415           | >99.9% | 26.1421          | >99.9% | 58                |
| H-9        | HWAVG3    | TWAVG5    | 5.0076                                                  | >99.9% | 2.8455           | 99.3%  | 20.4316          | >99.9% | 58                |
| H-10       | HWAVG3    | TWAVG5    | 5.2956                                                  | >99.9% | 3.2526           | 99.7%  | 22.8373          | >99.9% | 58                |
| H-11       | HWAVG3    | TWAVG5    | 6.4363                                                  | >99.9% | 4.1143           | >99.9% | 26.4070          | >99.9% | 58                |
| H-12       | HWAVG3    | TWAVG5    | 6.1778                                                  | >99.9% | 3.7576           | >99.9% | 25.6270          | >99.9% | 58                |
| H-13       | HWAVG3    | TWAVG5    | 5.3789                                                  | >99.9% | 2.4552           | 98.1%  | 21.4742          | >99.9% | 58                |
| H-14       | HWAVG3    | TWAVG5    | 5.4386                                                  | >99.9% | 1.3204           | 80.6%  | 22.4023          | >99.9% | 58                |
| H-15       | HWAVG3    | TWAVG5    | 5.4666                                                  | >99.9% | 3.4974           | >99.9% | 24.7969          | >99.9% | 58                |
| H-16       | HWAVG3    | TWAVG3    | 4.1764                                                  | >99.9% | 3.0182           | 99.6%  | 19.0158          | >99.9% | 58                |
| H-17       | HWAVG3    | TWAVG5    | 5.6490                                                  | >99.9% | 3.2076           | 99.7%  | 23.8186          | >99.9% | 58                |
| H-18       | HWAVG3    | TWAVG5    | 5.0825                                                  | >99.9% | 1.4351           | 83.7%  | 16.1686          | >99.9% | 58                |
| H-19       | HWAVG3    | TWAVG5    | 3.8786                                                  | >99.9% | 2.6630           | >99.0% | 17.9908          | >99.9% | 58                |
| H-20       | HWAVG3    | TWAVG5    | 5.3083                                                  | >99.9% | 2.3154           | 97.5%  | 19.5634          | >99.9% | 58                |
| H-21       | HWAVG3    | TWAVG5    | 5.0758                                                  | >99.9% | 2.0361           | 95.3%  | 20.6968          | >99.9% | 58                |
| H-22       | HWAVG3    | TW4TO6    | 1.4486                                                  | 84.0%  | 0.8988           | 62.2%  | 7.0162           | >99.9% | 58                |
| H-25       | HWAVG3    | TW4TO6    | 1.4728                                                  | 84.1%  | 1.0558           | 68.7%  | 6.0675           | >99.9% | 30                |

<sup>a</sup>t for  $H_0$ :Parameter = 0 and the degree of confidence (D.C.) that  $H_1$ :Parameter = 0 is true (see definition of hypothesis, p. 118).

# STANDARDIZED RESIDUALS—PIEZOMETER AD-2

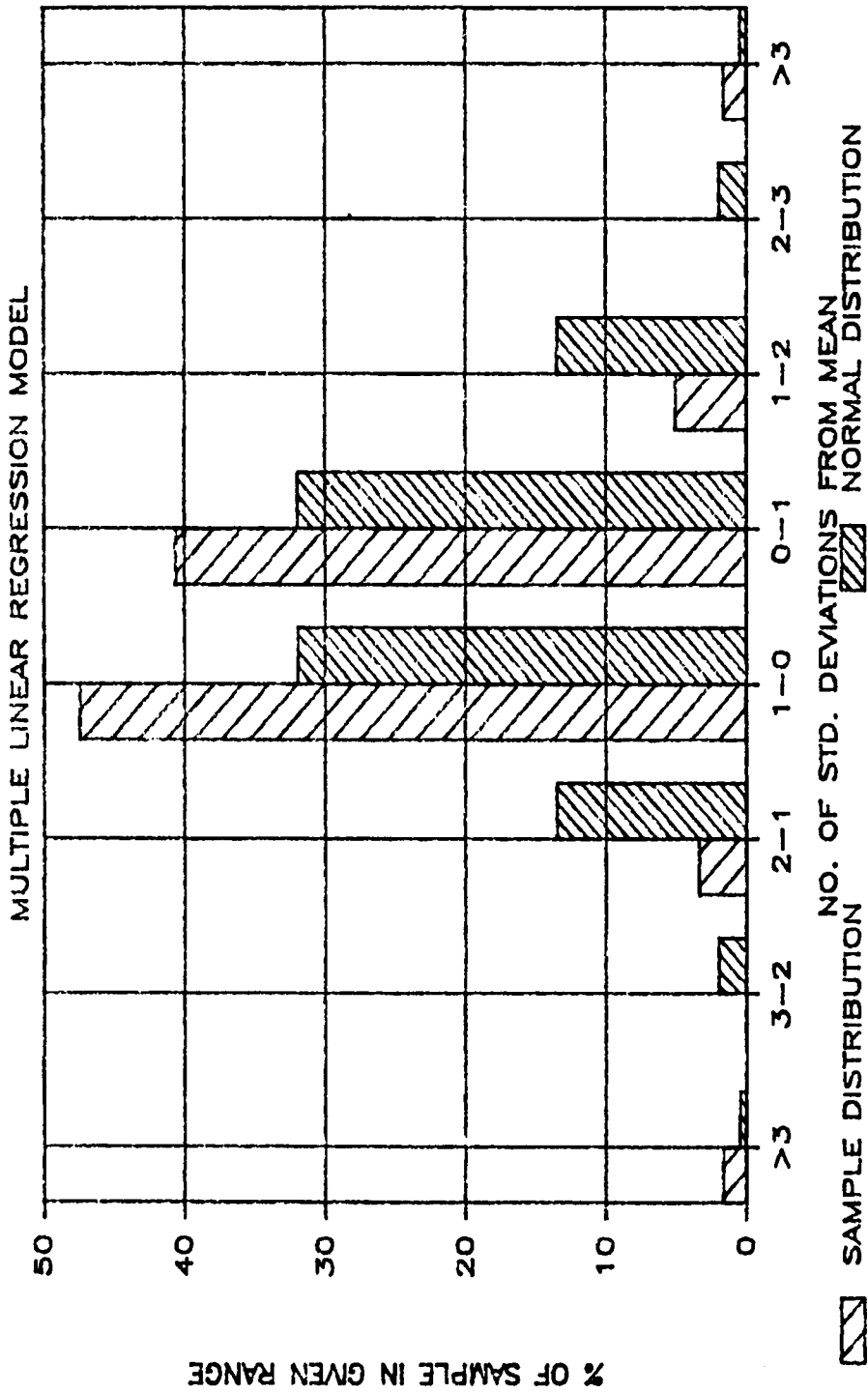


FIGURE A-1. COMPARISON OF THE MULTIPLE REGRESSION MODEL ERROR DISTRIBUTION FOR PIEZOMETER AD-2 WITH THE STANDARD NORMAL

# STANDARDIZED RESIDUALS—PIEZOMETER H-1

MULTIPLE LINEAR REGRESSION MODEL

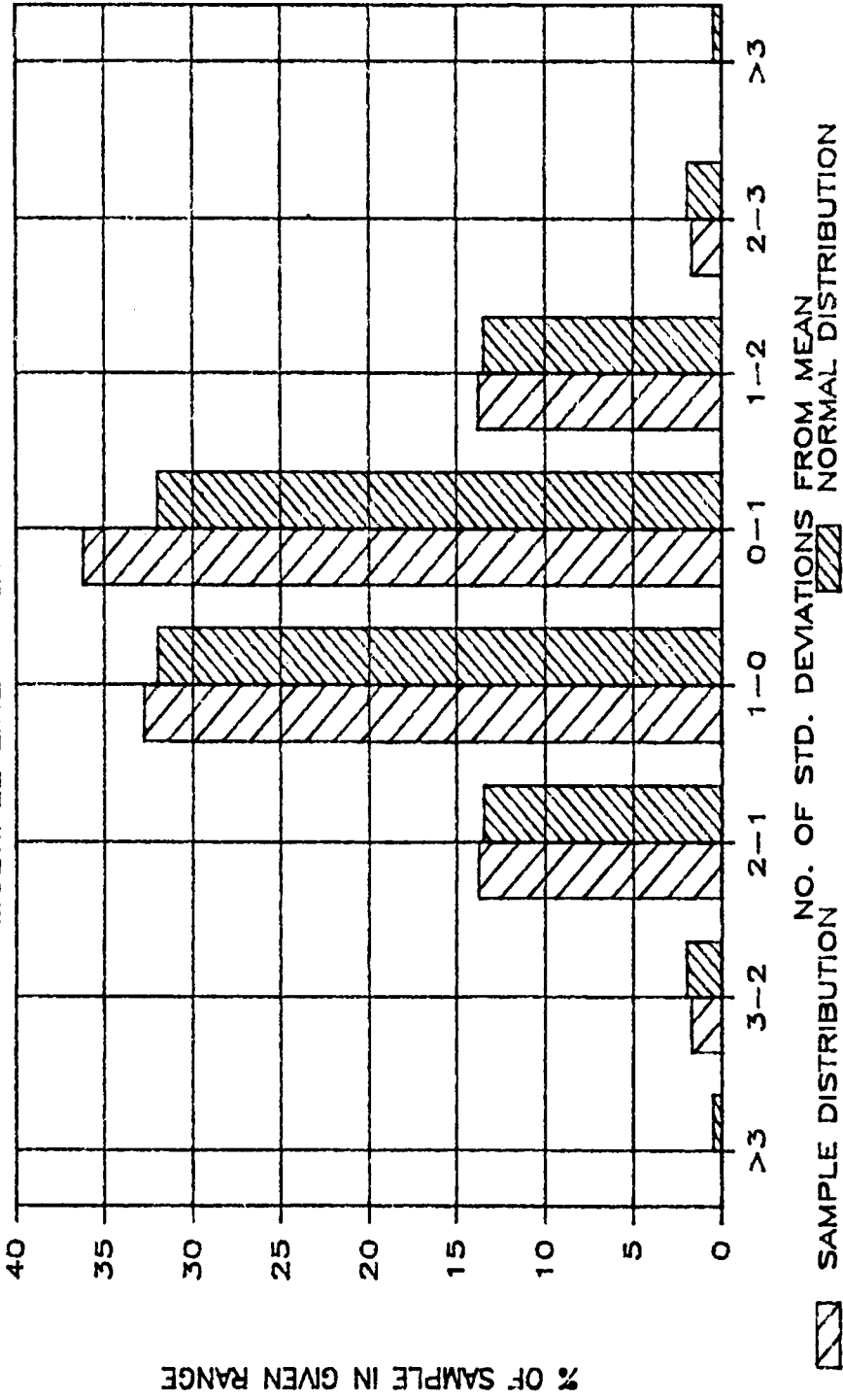


FIGURE A-2. COMPARISON OF THE MULTIPLE REGRESSION MODEL ERROR DISTRIBUTION FOR PIEZOMETER H-1 WITH THE STANDARD NORMAL

# REGRESSION MODEL : PIEZOMETER AU-1

AU-1 -- -142.5 + 1.172\*HW10TO12 - .0155\*TWAVG3

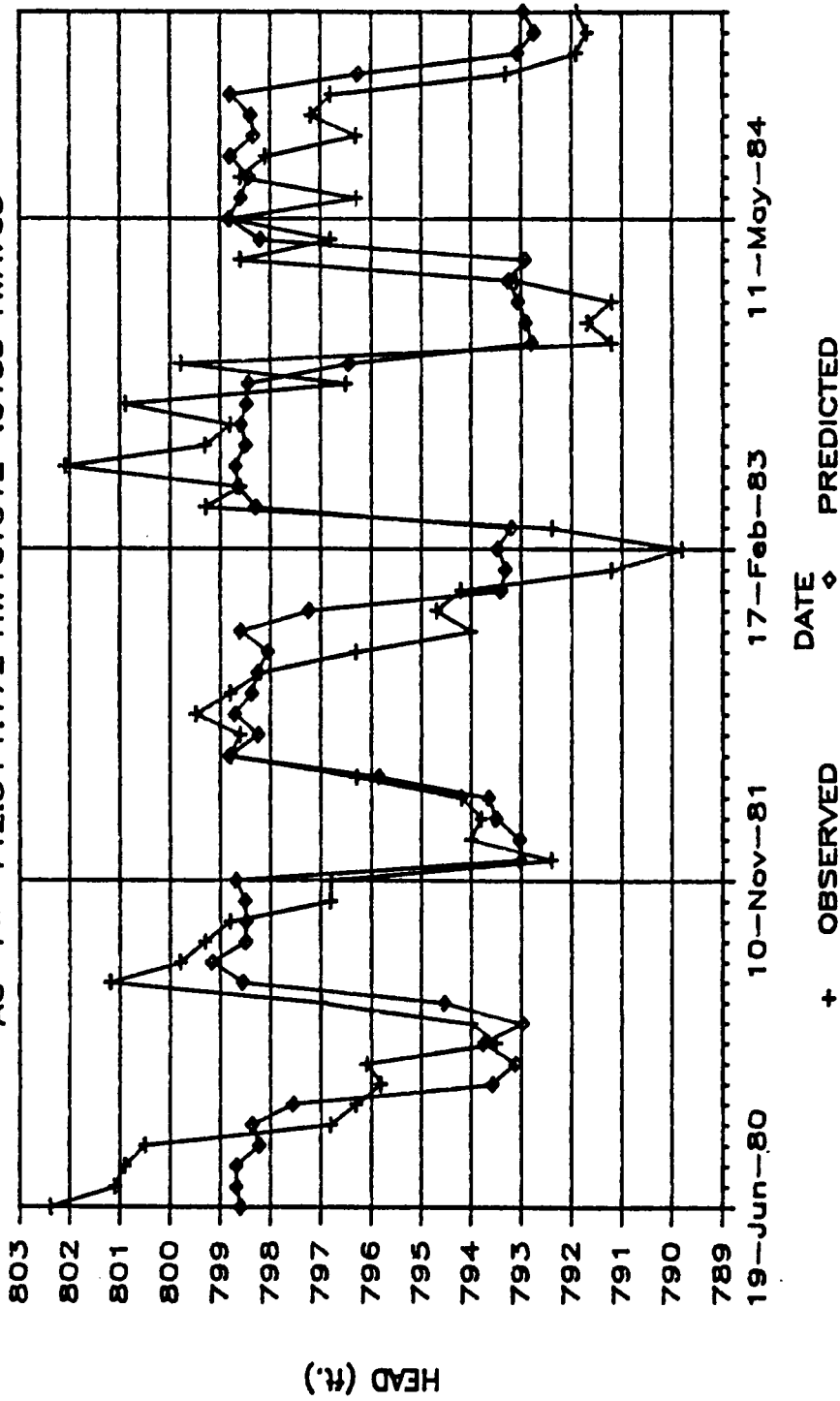


FIGURE A-3. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AU-1

# REGRESSION MODEL : PIEZOMETER AU-2

$$AU-2 = -68.78 + 0.908 \cdot HWAVG3 + 0.182 \cdot TWAVG30$$

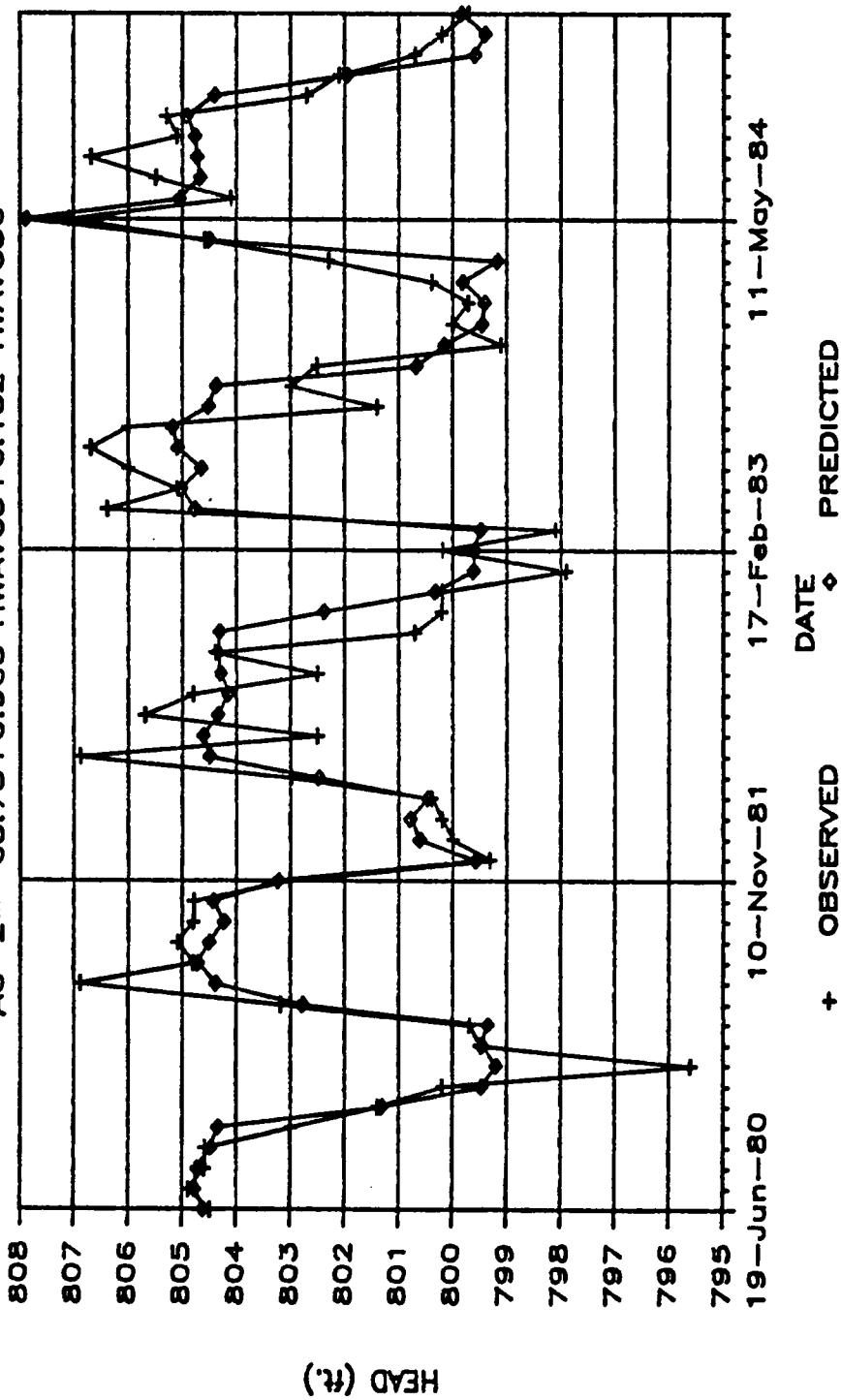


FIGURE A-4. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AU-2

# REGRESSION MODEL : PIEZOMETER AU-3

$$AU-3 = -92.44 + 1.219 \cdot HW - 0.010 \cdot TWAVG30$$

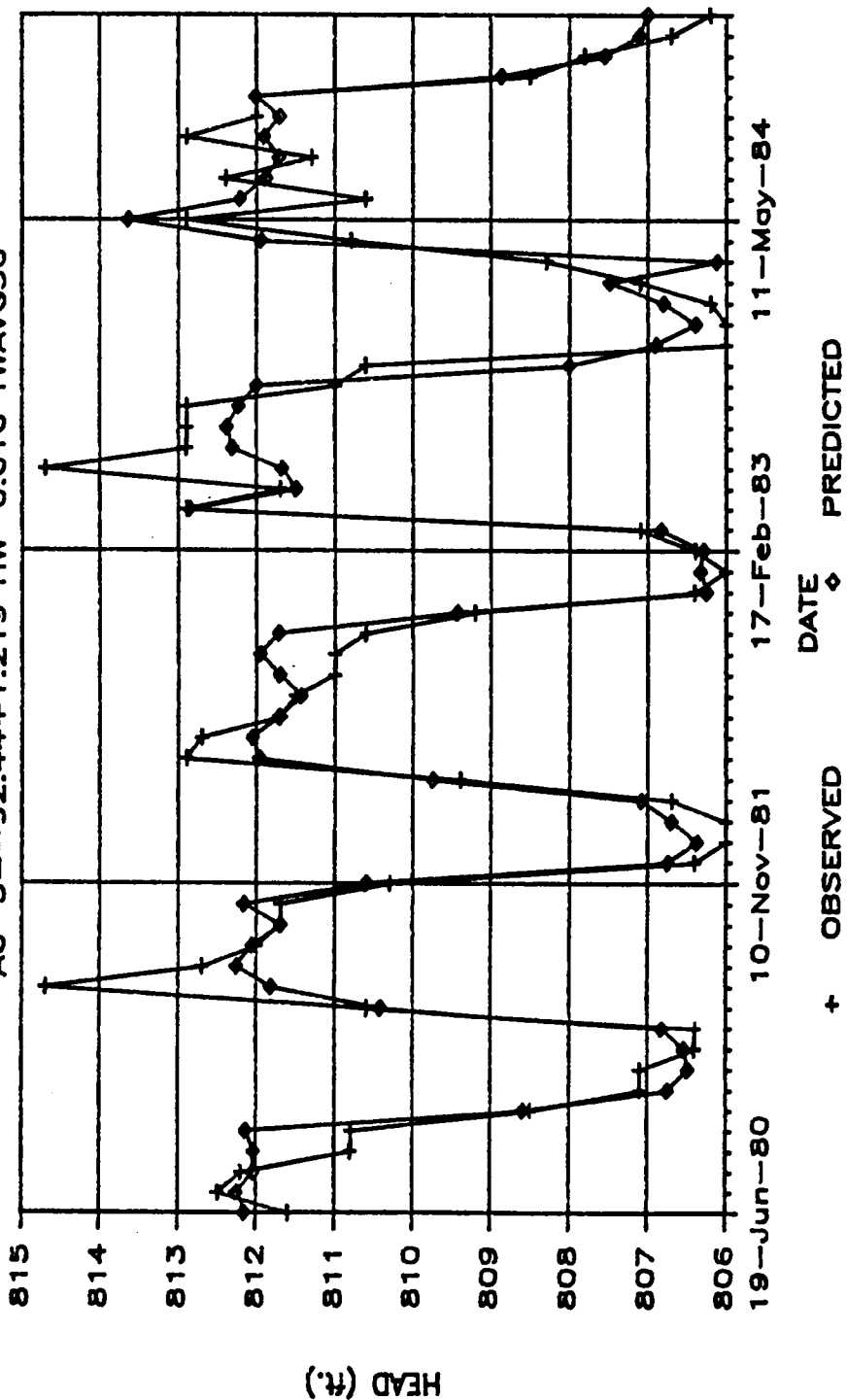


FIGURE A-5. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AU-3

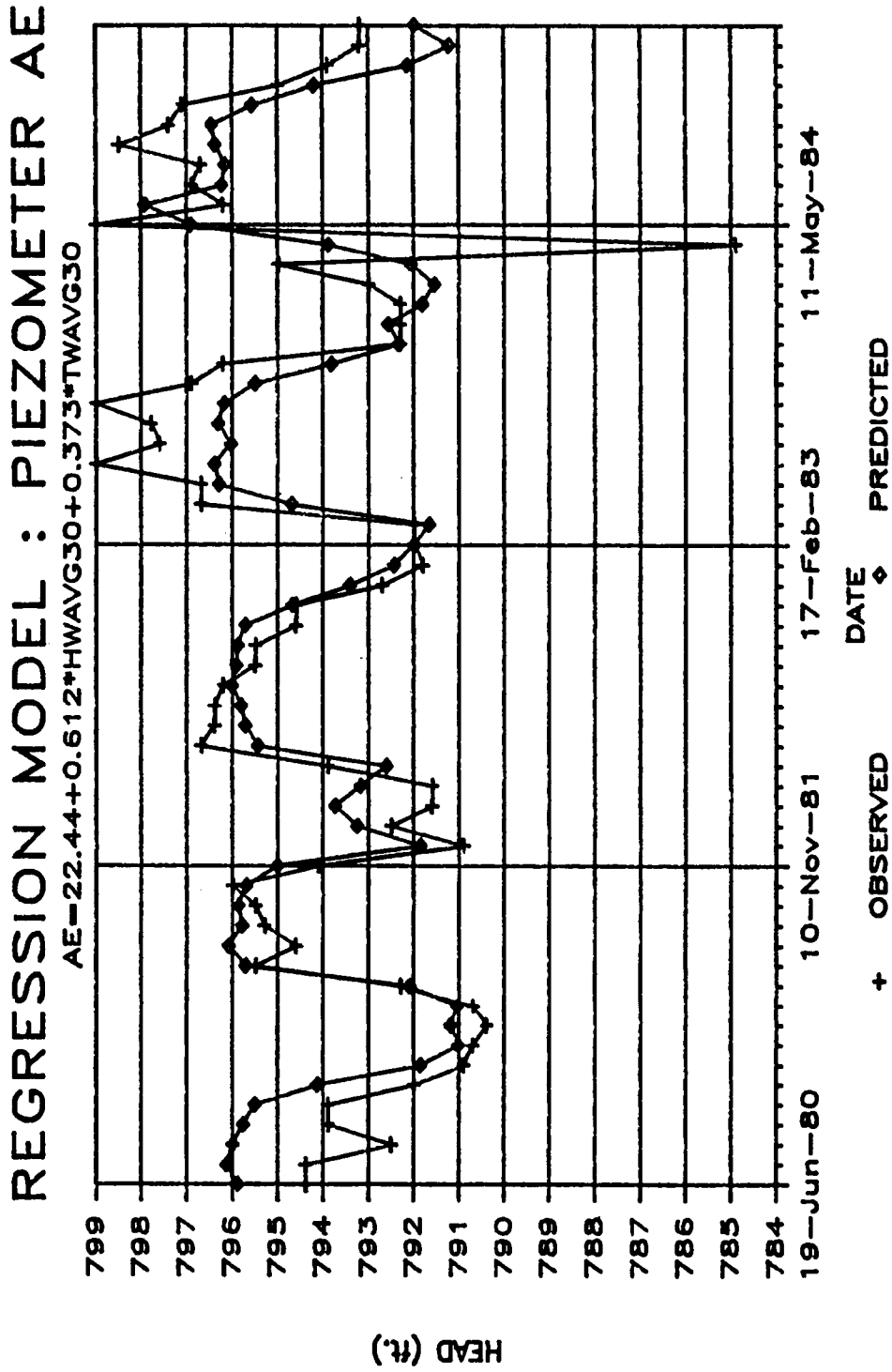


FIGURE A-6. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AE

# REGRESSION MODEL : PIEZOMETER AD-1

$$AD-1 = 162.24 + 0.338 * HWAVG3 + 0.412 * TWAVG3$$

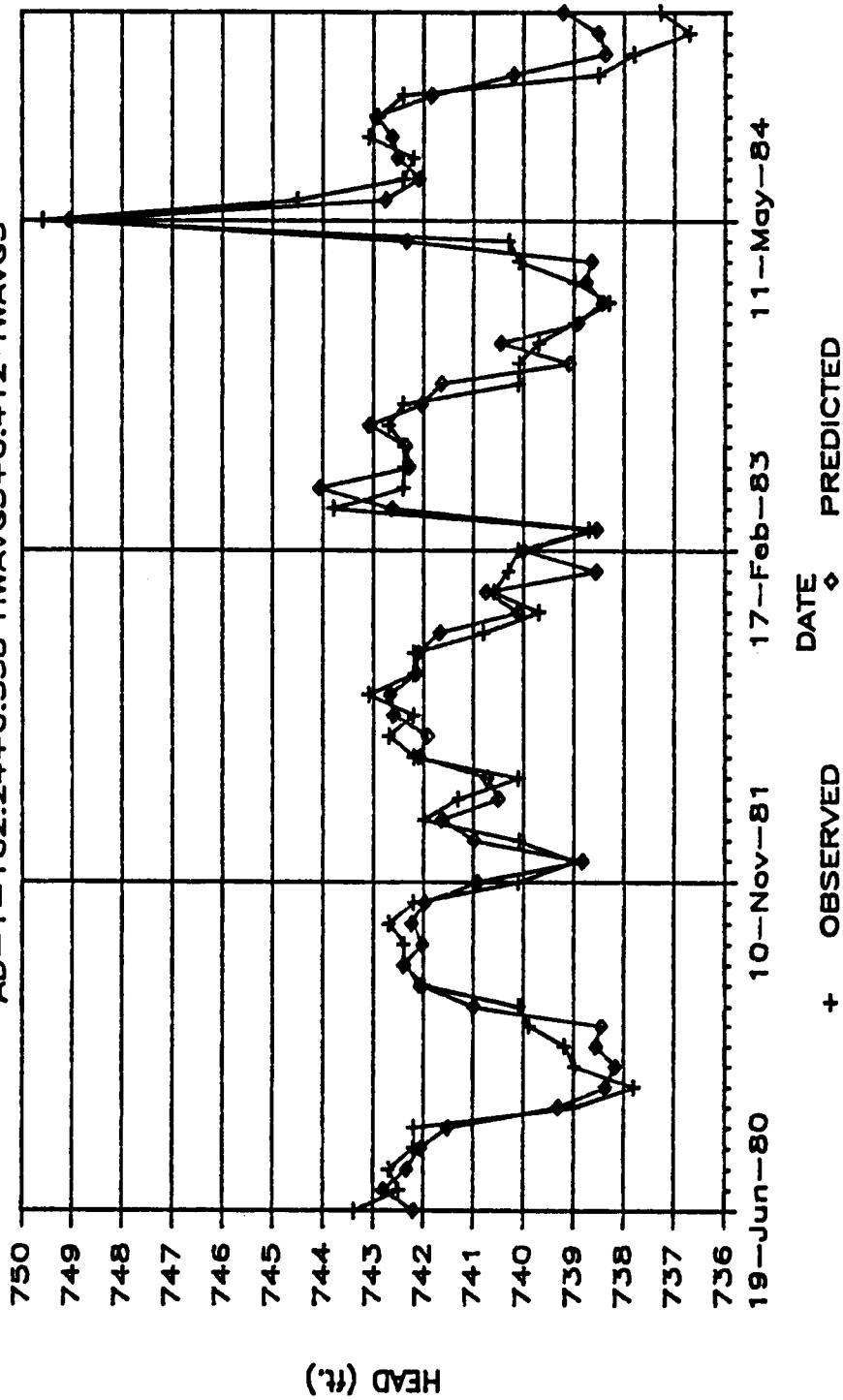


FIGURE A-7. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AD-1

# REGRESSION MODEL : PIEZOMETER AD-2

$$AD-2 = 208.01 + 0.159 \cdot HWAVG3 + 0.545 \cdot TWAVG10$$

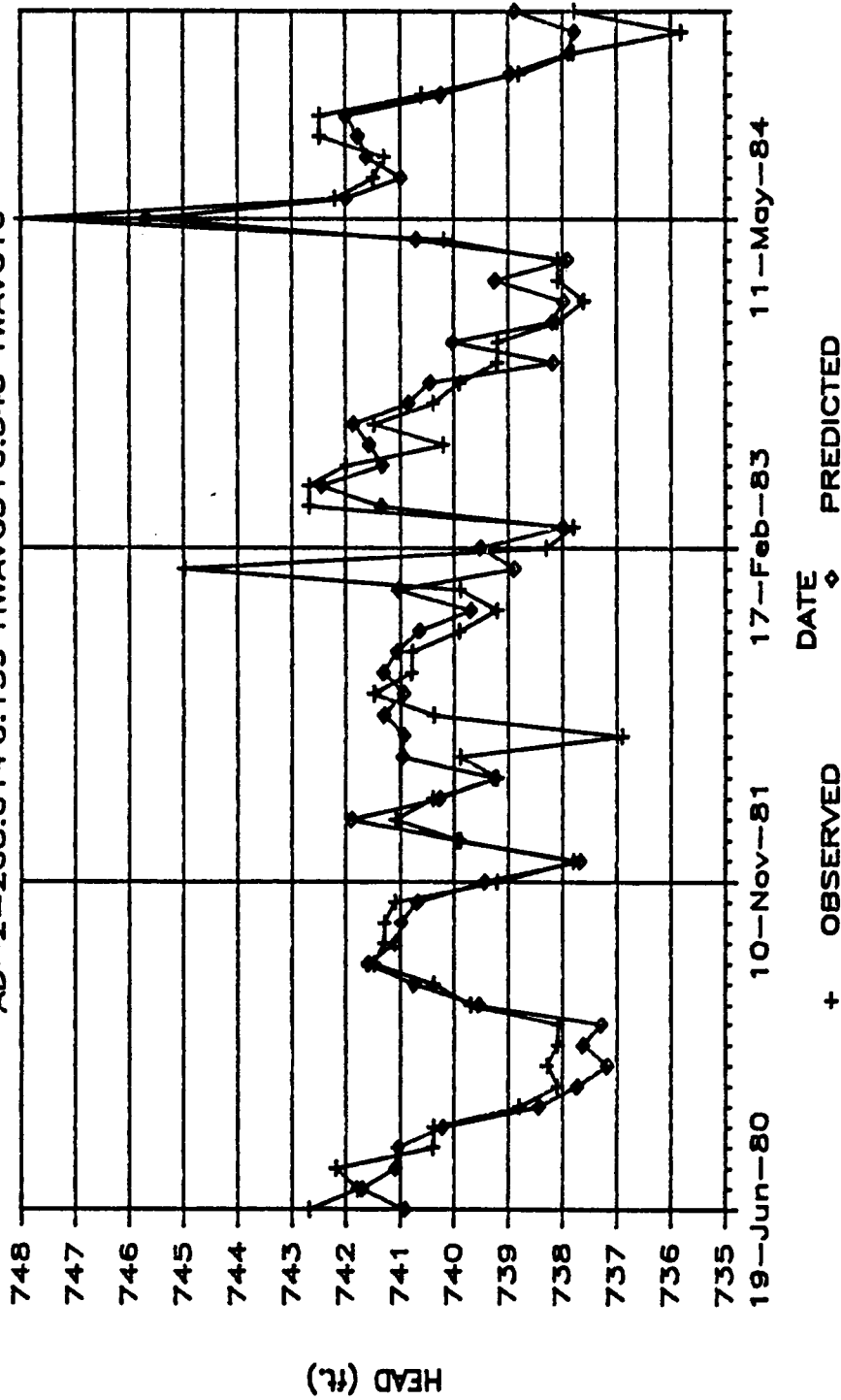


FIGURE A-8. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AD-2

# REGRESSION MODEL : PIEZOMETER AD-3

$$AD-3 = 250.38 + 0.014 \cdot HWAVG3 + 0.646 \cdot TWAVG10$$

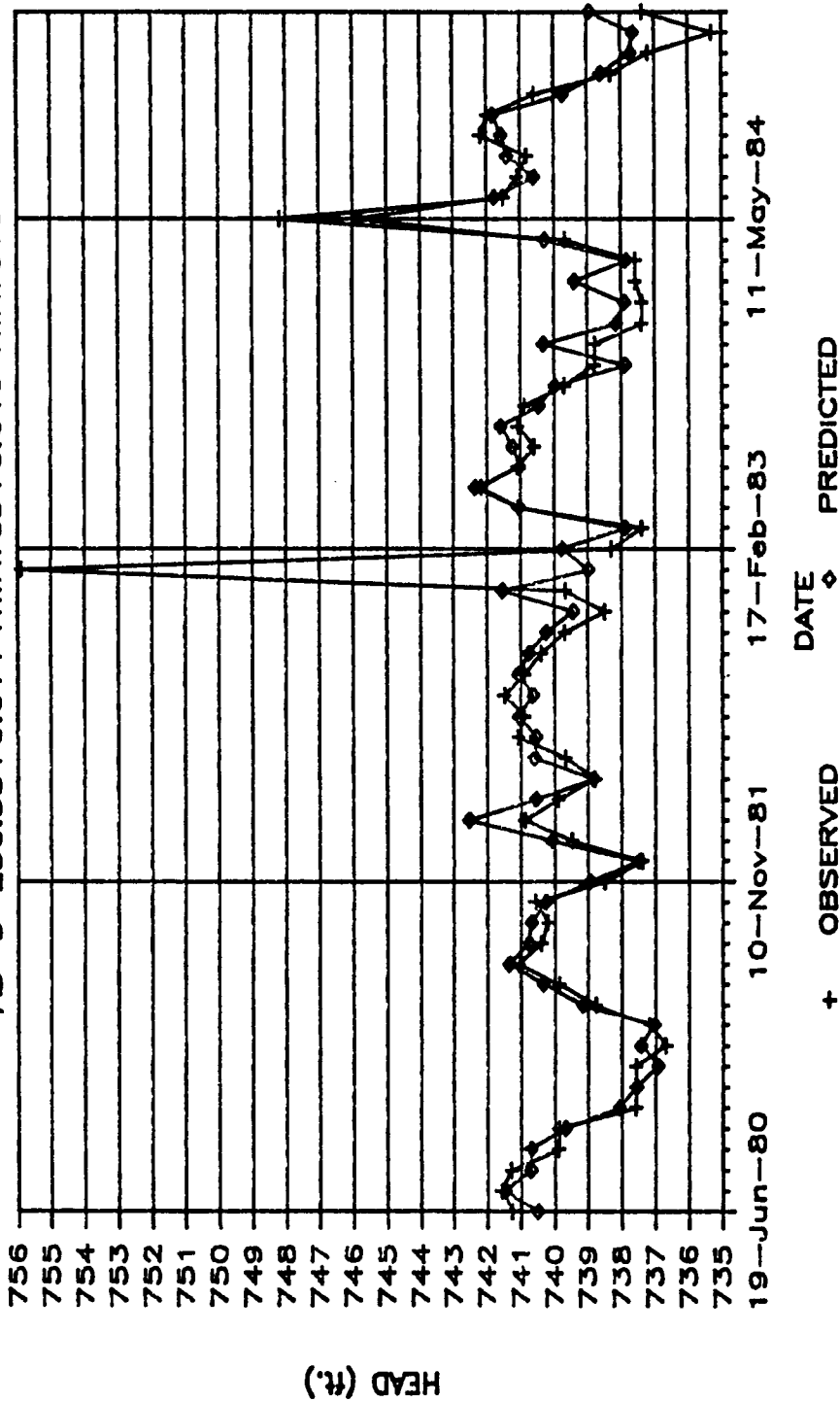


FIGURE A-9. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AD-3

# REGRESSION MODEL : PIEZOMETER AD-4

$$AD-4 = 49.62 + 0.416 * HWAVG3 + 0.476 * TWAVG3$$

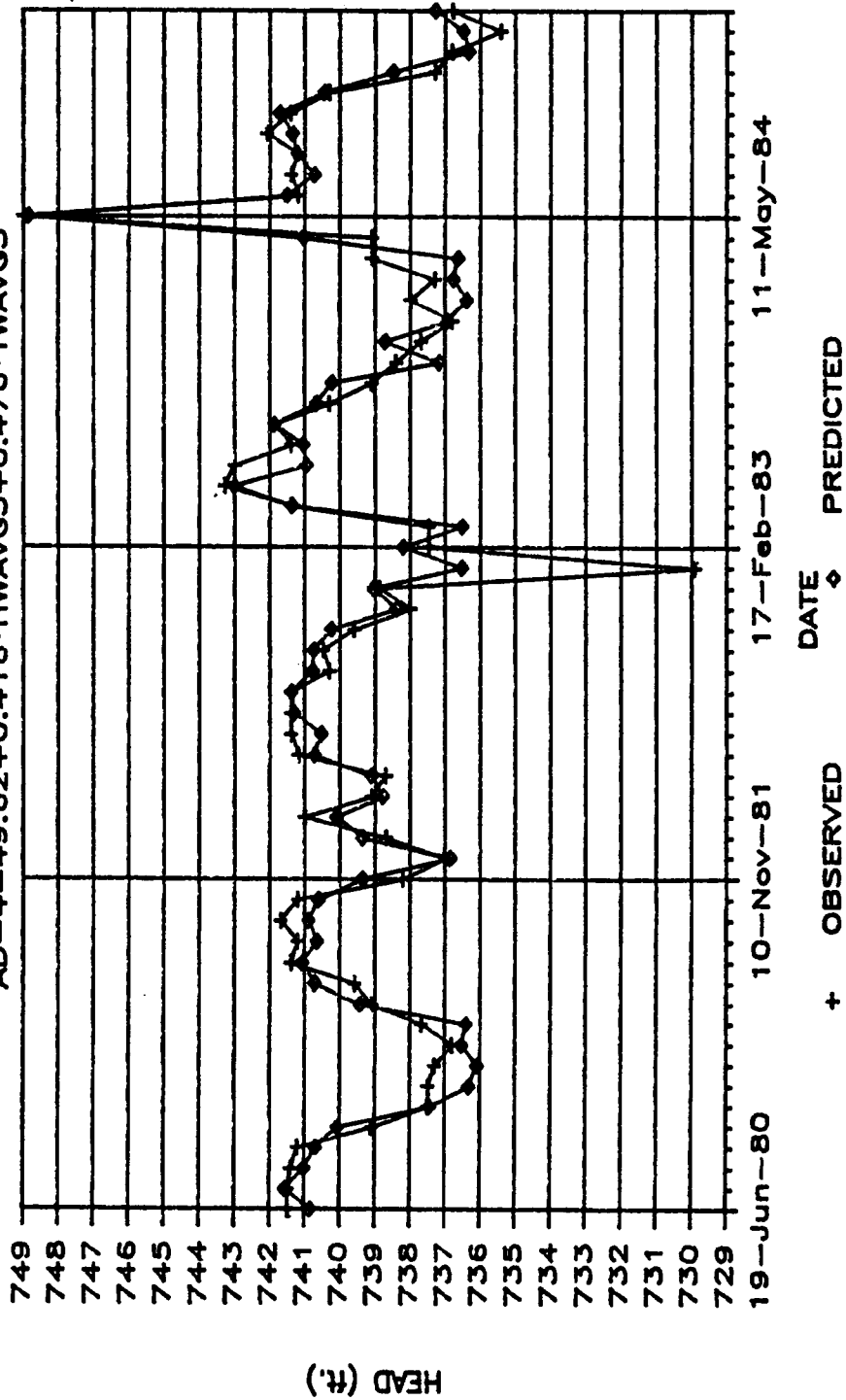


FIGURE A-10. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AD-4

# REGRESSION MODEL : PIEZOMETER AD-5

$AD-5 = 144.38 + 0.290 * HWAVG3 + 0.484 * TWAVG5$

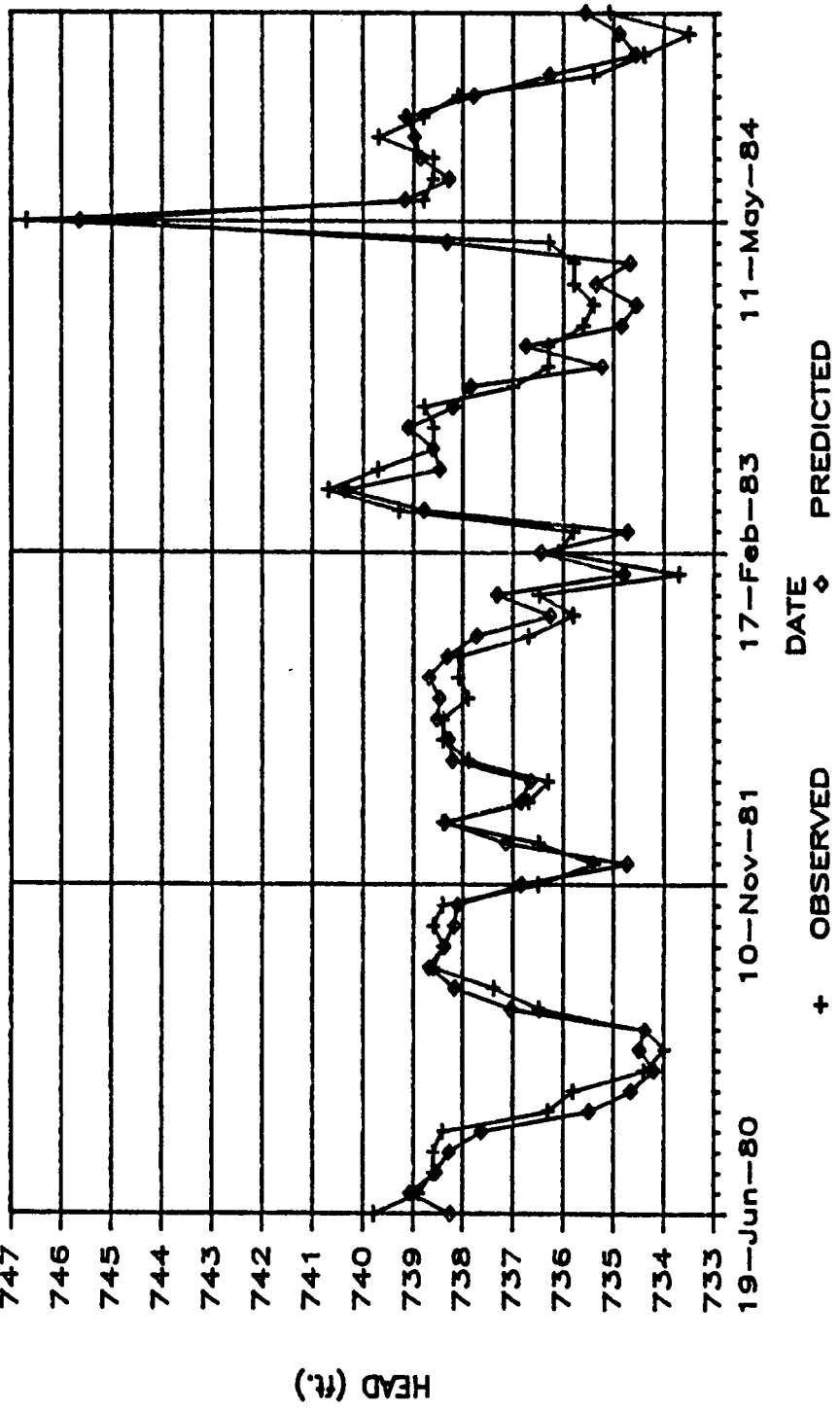


FIGURE A-11. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AD-5

# REGRESSION MODEL : PIEZOMETER AD-6

$$AD-6 = 148.96 + 0.298 * HWAVG3 + 0.471 * TWAVG5$$

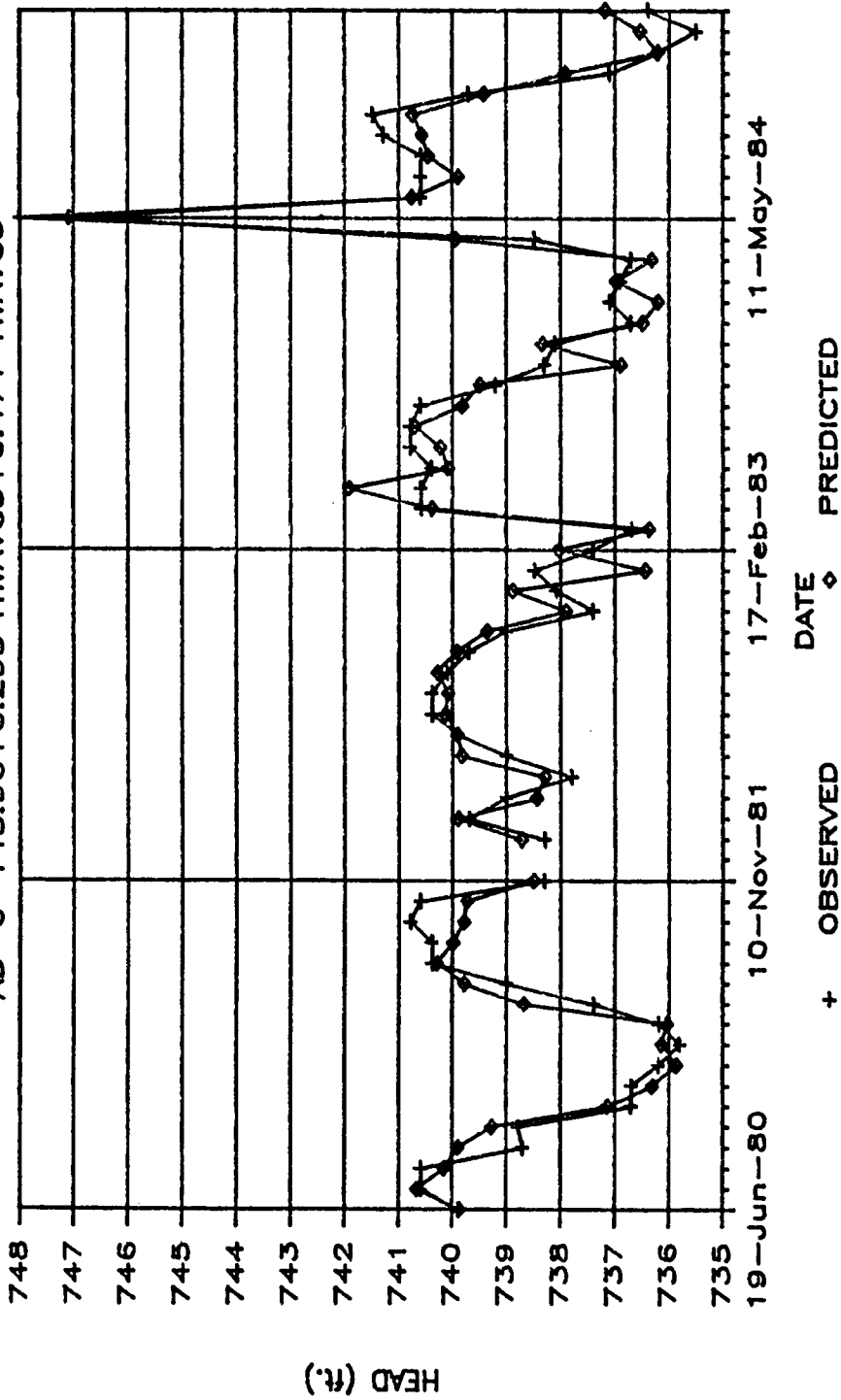


FIGURE A-12. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER AD-6

# REGRESSION MODEL : PIEZOMETER BU-1

$$BU-1 = 131.35 + 0.554 * HWAVG3 + 0.240 * TWAVG5$$

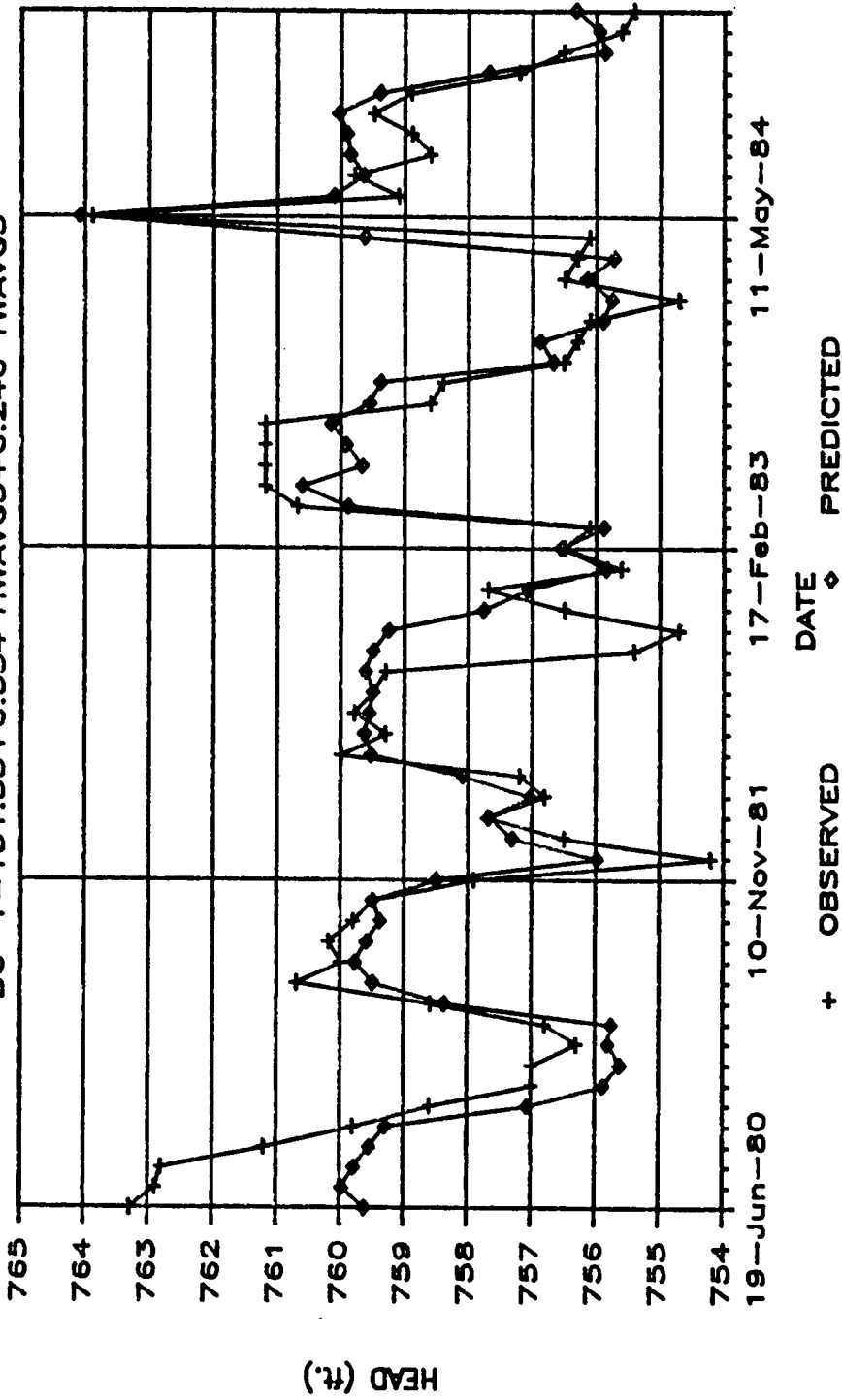


FIGURE A-13. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BU-1

# REGRESSION MODEL : PIEZOMETER BU-2

BU-2=717.2+0.431\*HWAVG30-0.382\*TW1OTO12

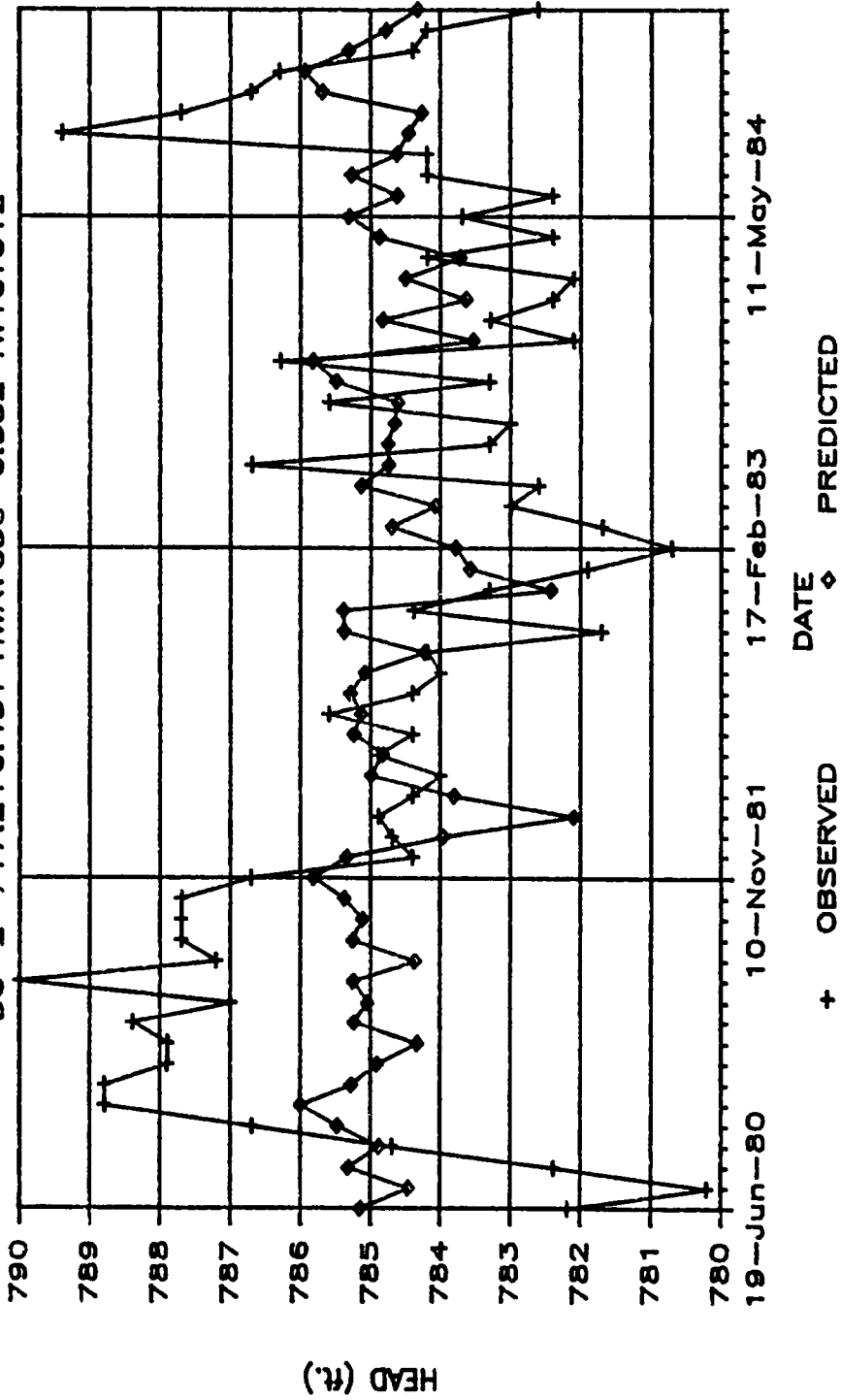


FIGURE A-14. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BU-2

# REGRESSION MODEL : PIEZOMETER BU-3

$$BU-3 = -15.05 + 0.964 \cdot HW + 0.056 \cdot TWAVG30$$

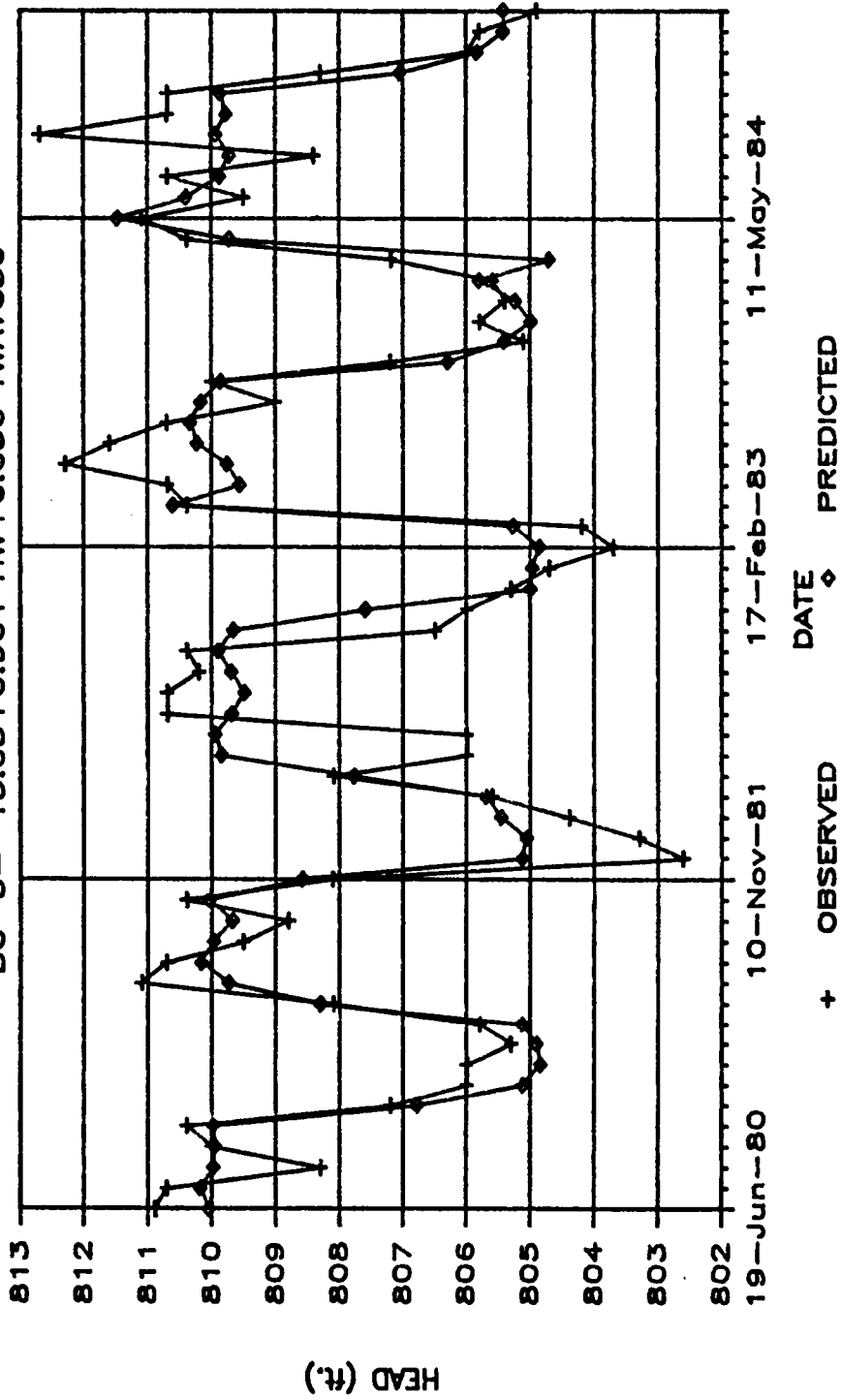


FIGURE A-15. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BU-3

# REGRESSION MODEL : PIEZOMETER BE

$$BE = 193.36 + 0.616 \cdot HW10TO12 + 0.437 \cdot TWAVG5$$

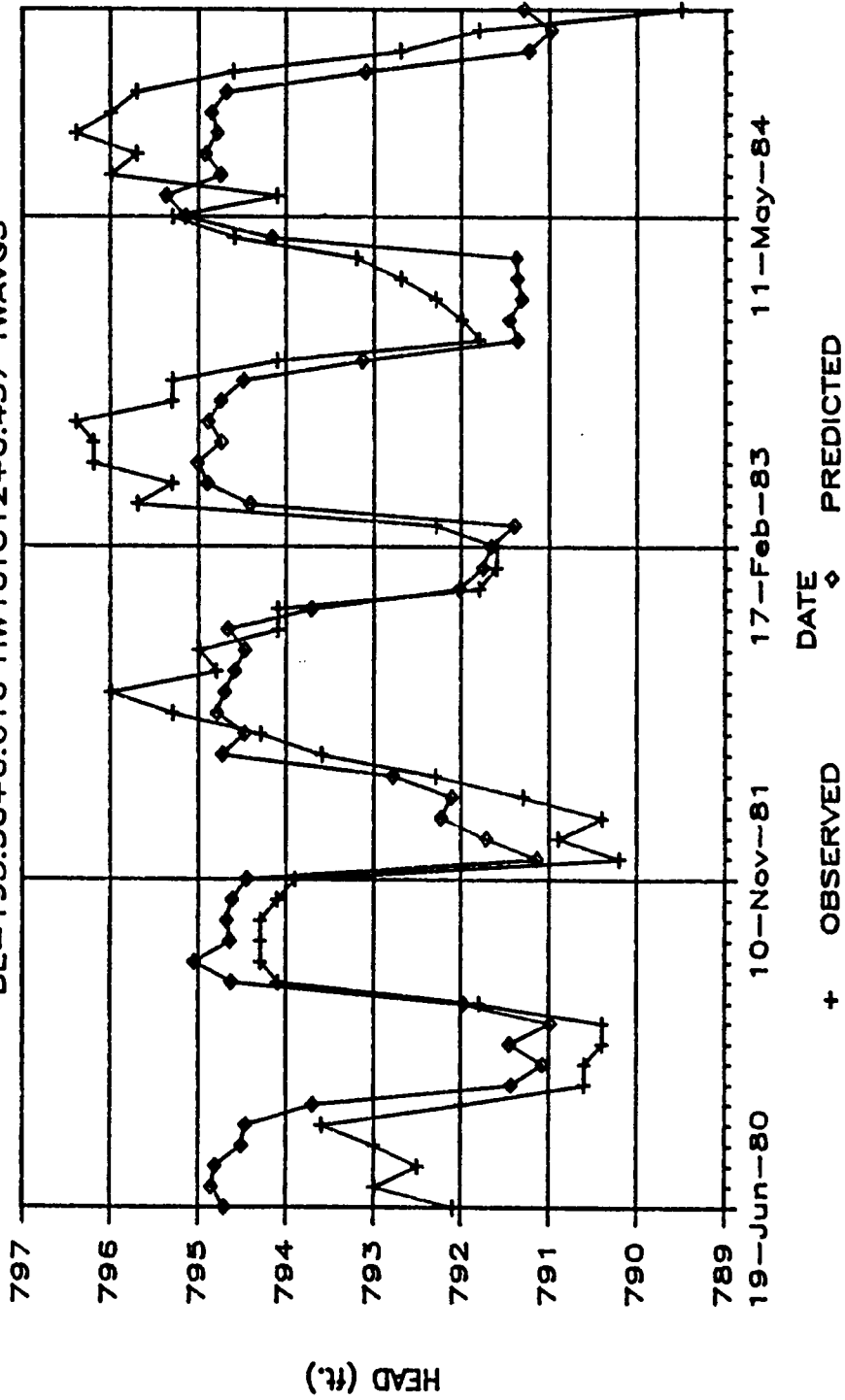


FIGURE A-16. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BE

# REGRESSION MODEL : PIEZOMETER BD-1

$$BD-1 = 70.61 + 0.380 * HWAVG3 + 0.494 * TWAVG10$$

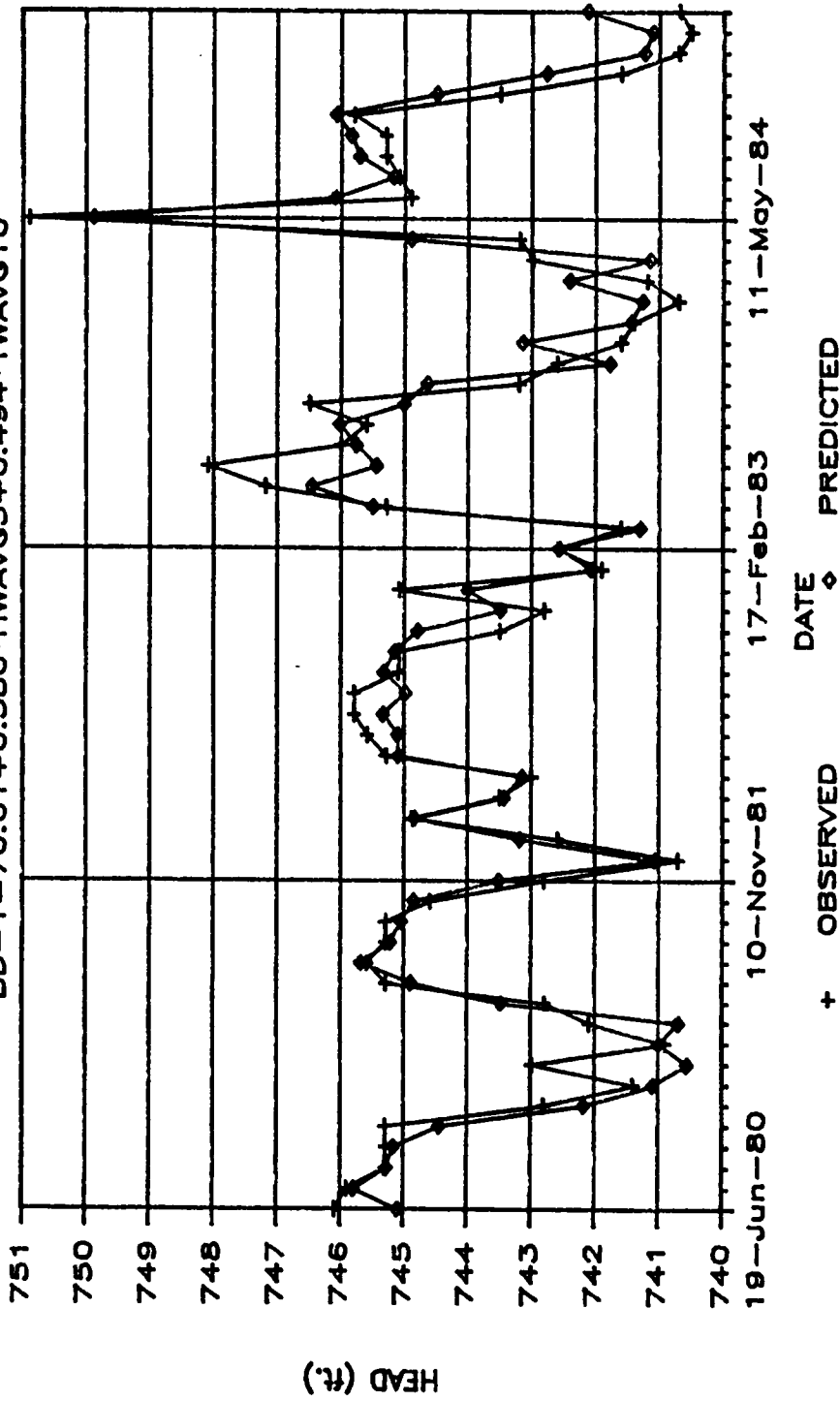


FIGURE A-17. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BD-1

REGRESSION MODEL : PIEZOMETER BD-2

$BD-2=181.84+0.294*HWAVG10+0.437*TWAVG5$

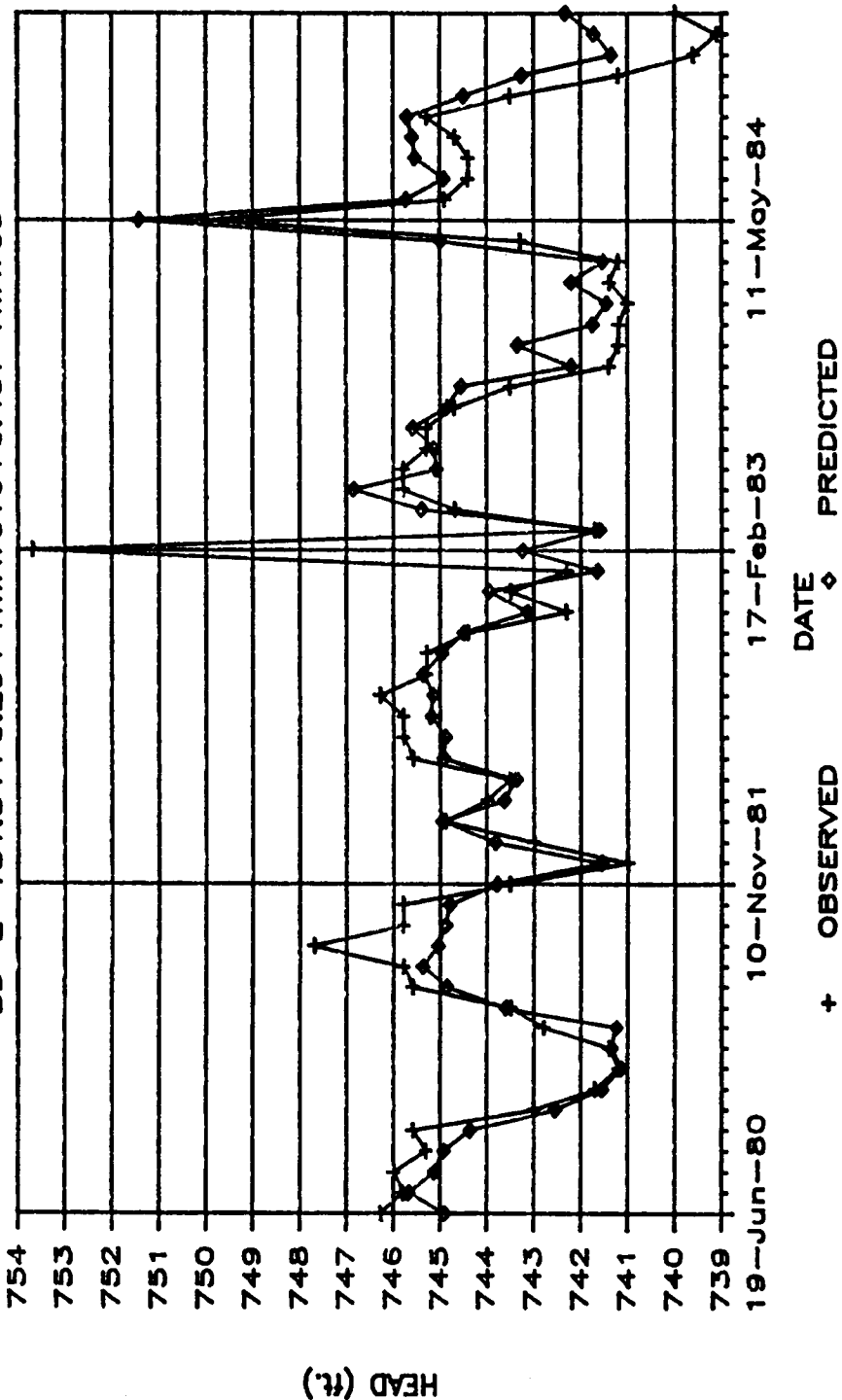


FIGURE A-18. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BD-2

REGRESSION MODEL : PIEZOMETER BD-3

$BD-3 = 138.18 + 0.285 * HWAVG3 + 0.499 * TWAVG10$

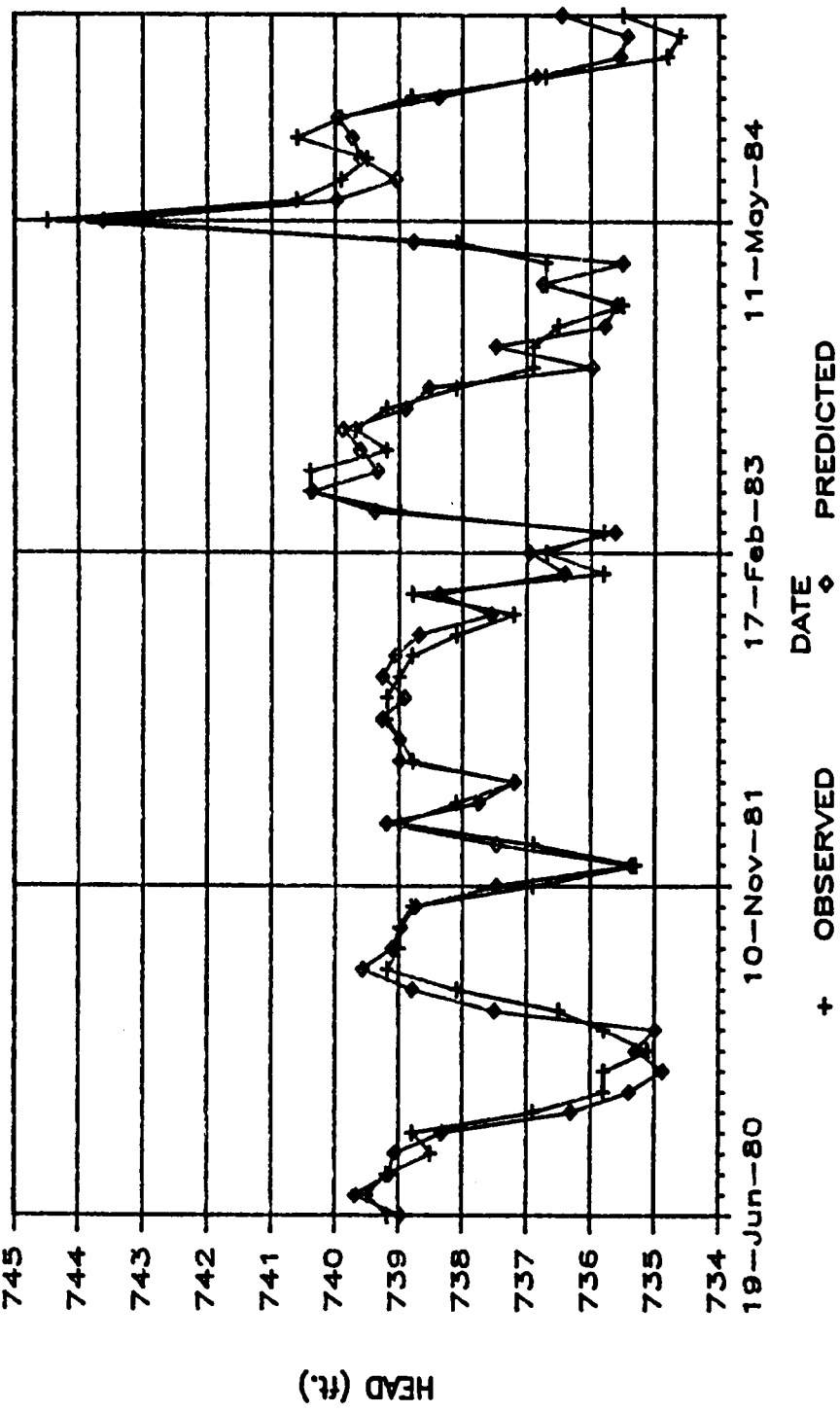


FIGURE A-19. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BD-3

# REGRESSION MODEL : PIEZOMETER BD-4

$$BD-4 = 9.74 + 0.324 * HWAVG3 + 0.632 * TWAVG10$$

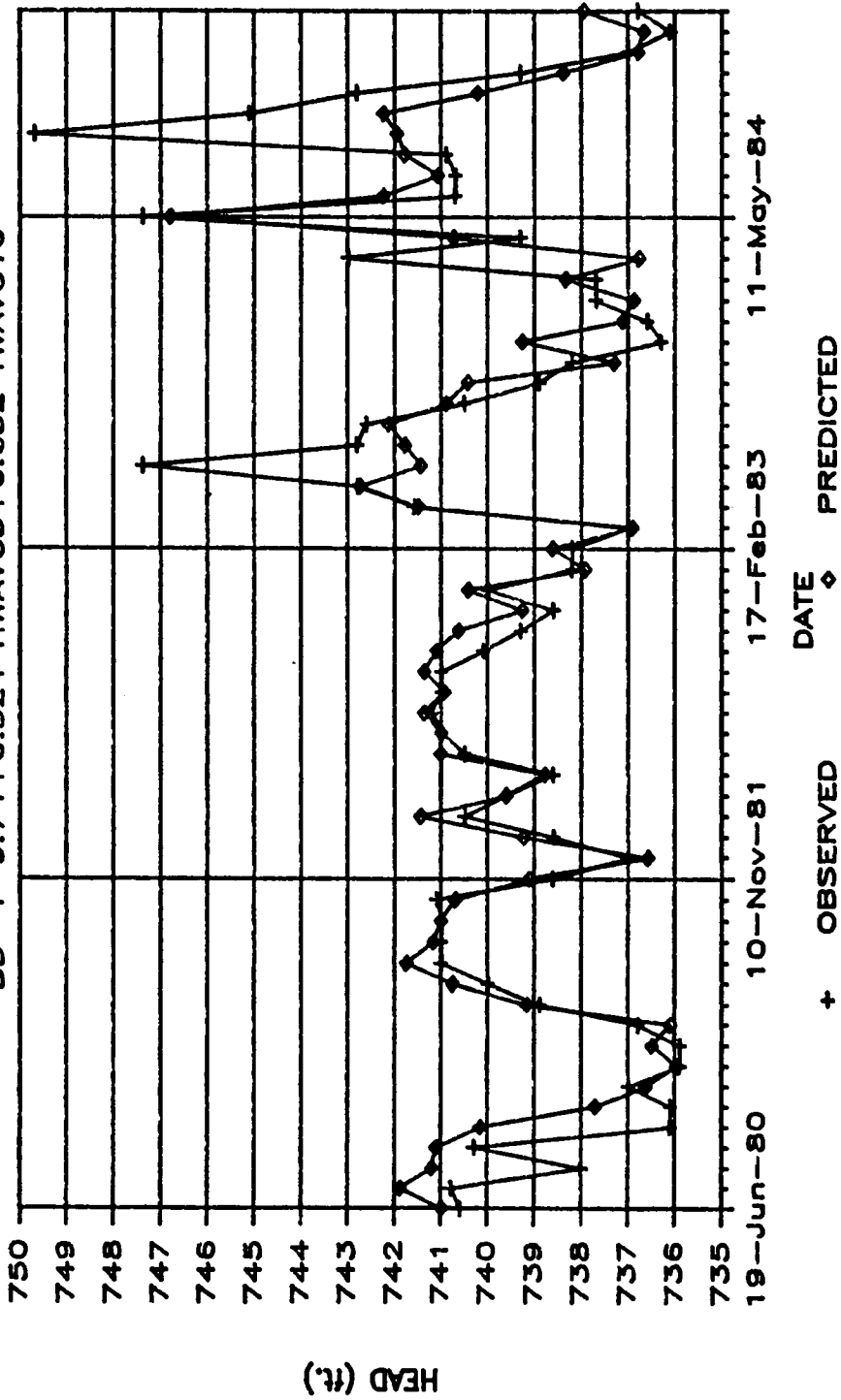


FIGURE A-20. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BD-4

# REGRESSION MODEL : PIEZOMETER BD-5

$$BD-5=101.28+0.2994*HWAVG3+0.536*TWAVG5$$

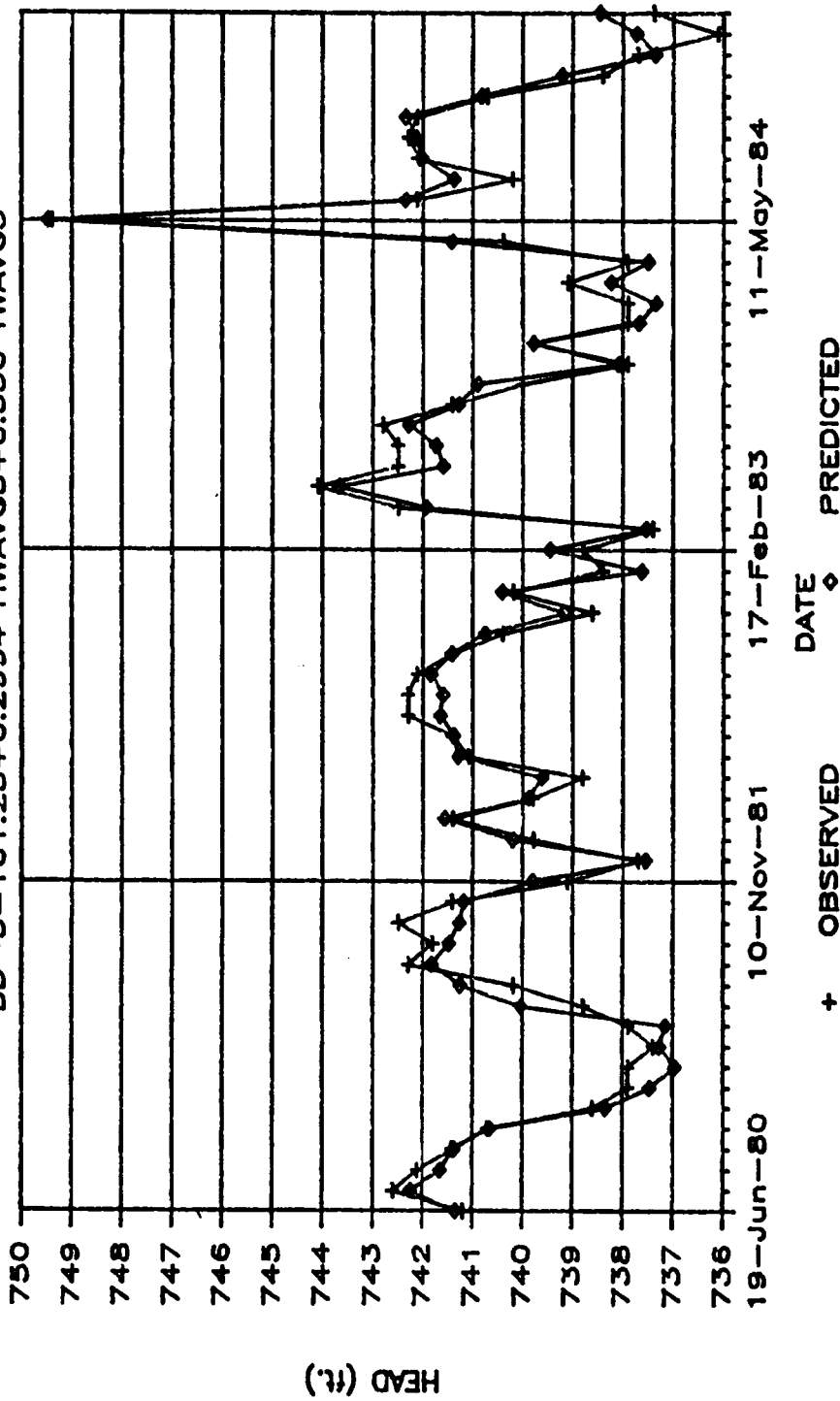


FIGURE A-21. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BD-5

# REGRESSION MODEL : PIEZOMETER BD-6

$$BD-6 = 159.94 * 0.343 * HWAVG3 + 0.407 * TWAVG10$$

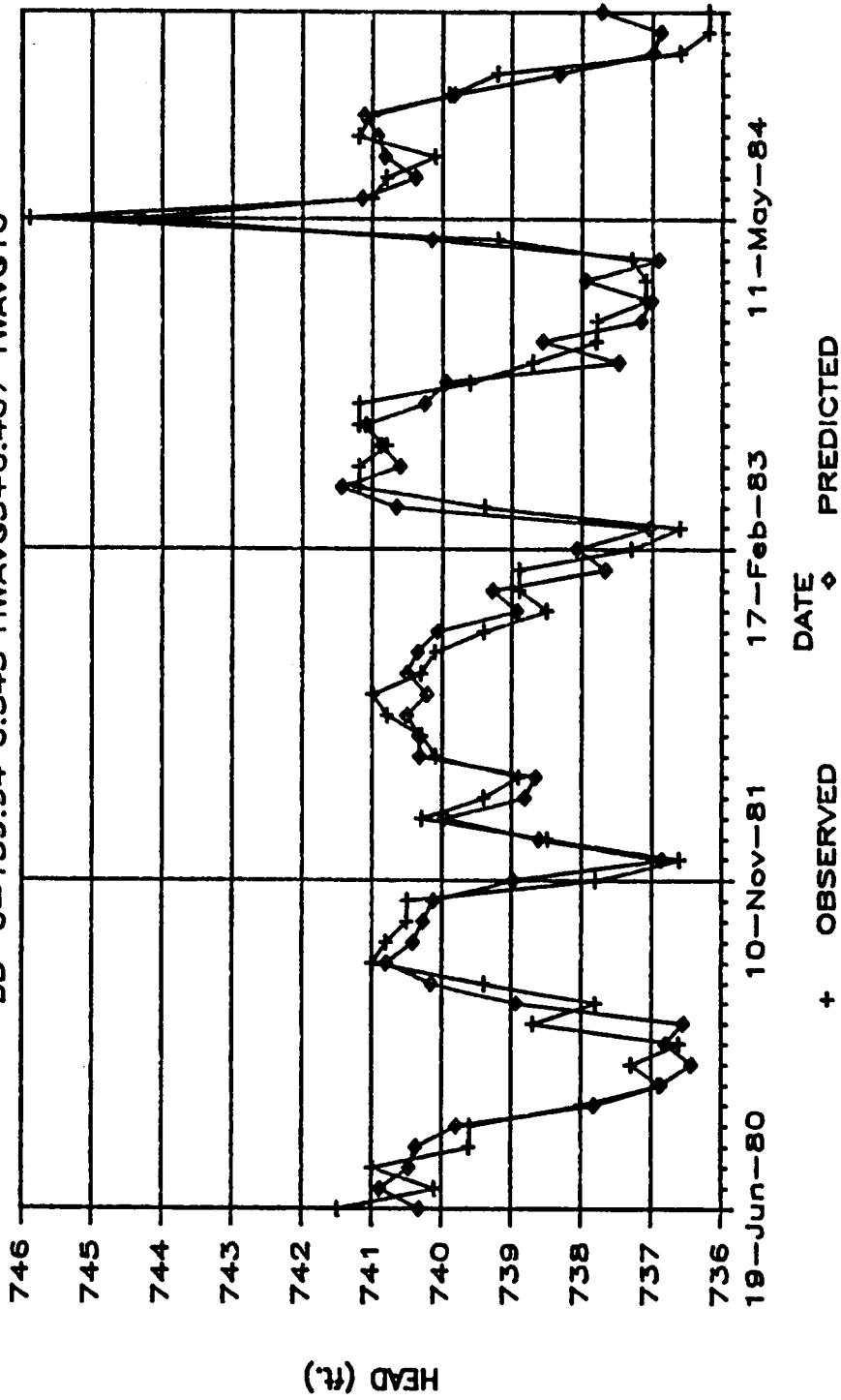


FIGURE A-22. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER BD-6

# REGRESSION MODEL : PIEZOMETER CU-1

$$CU-1 = -135.70 + 1.007 \cdot HW + 0.170 \cdot TWA \cdot VG30$$

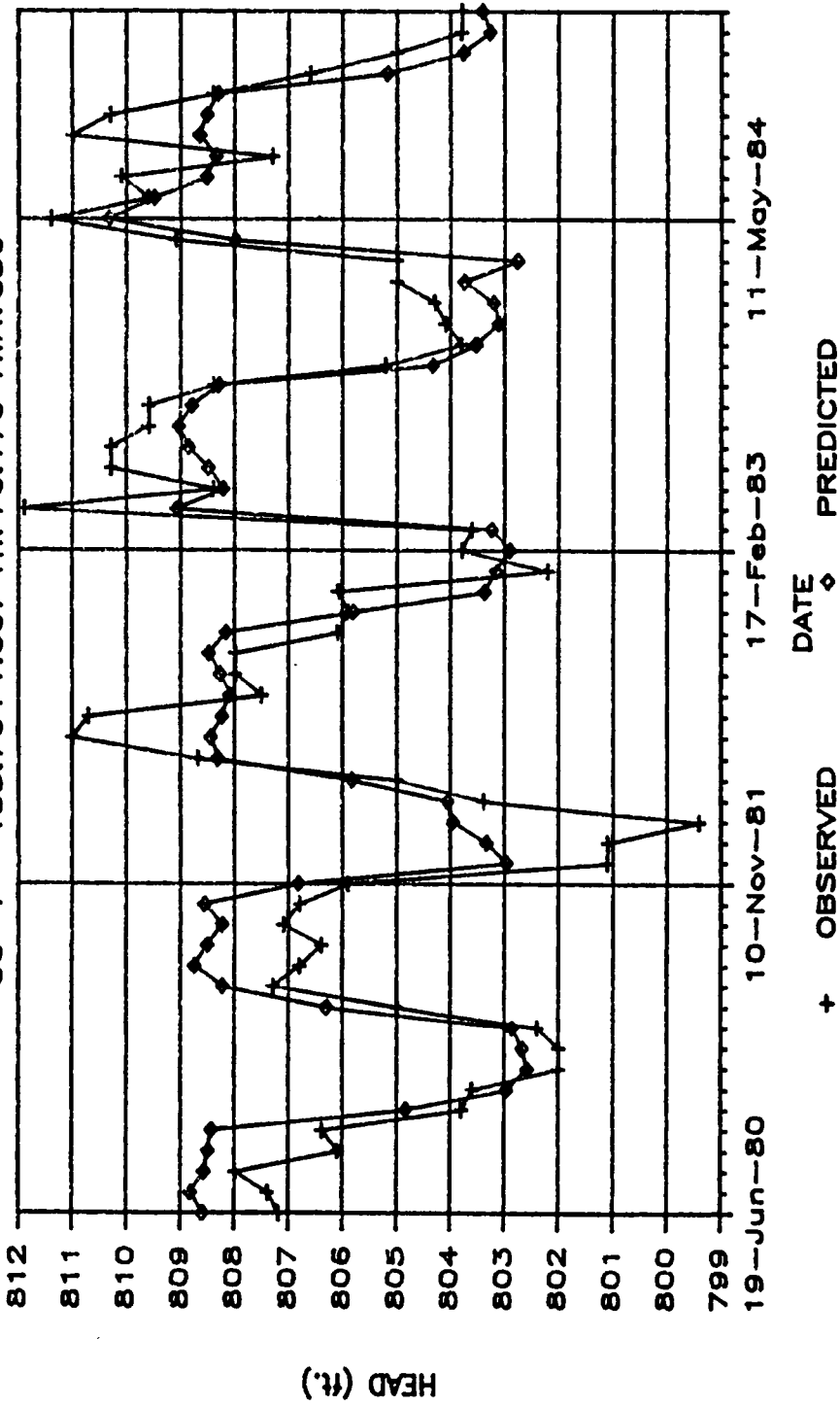


FIGURE A-23. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CU-1

# REGRESSION MODEL : PIEZOMETER CU-2

$$CU-2 = -158.54 + 0.9934 \cdot HW + 0.216 \cdot TWAVG30$$

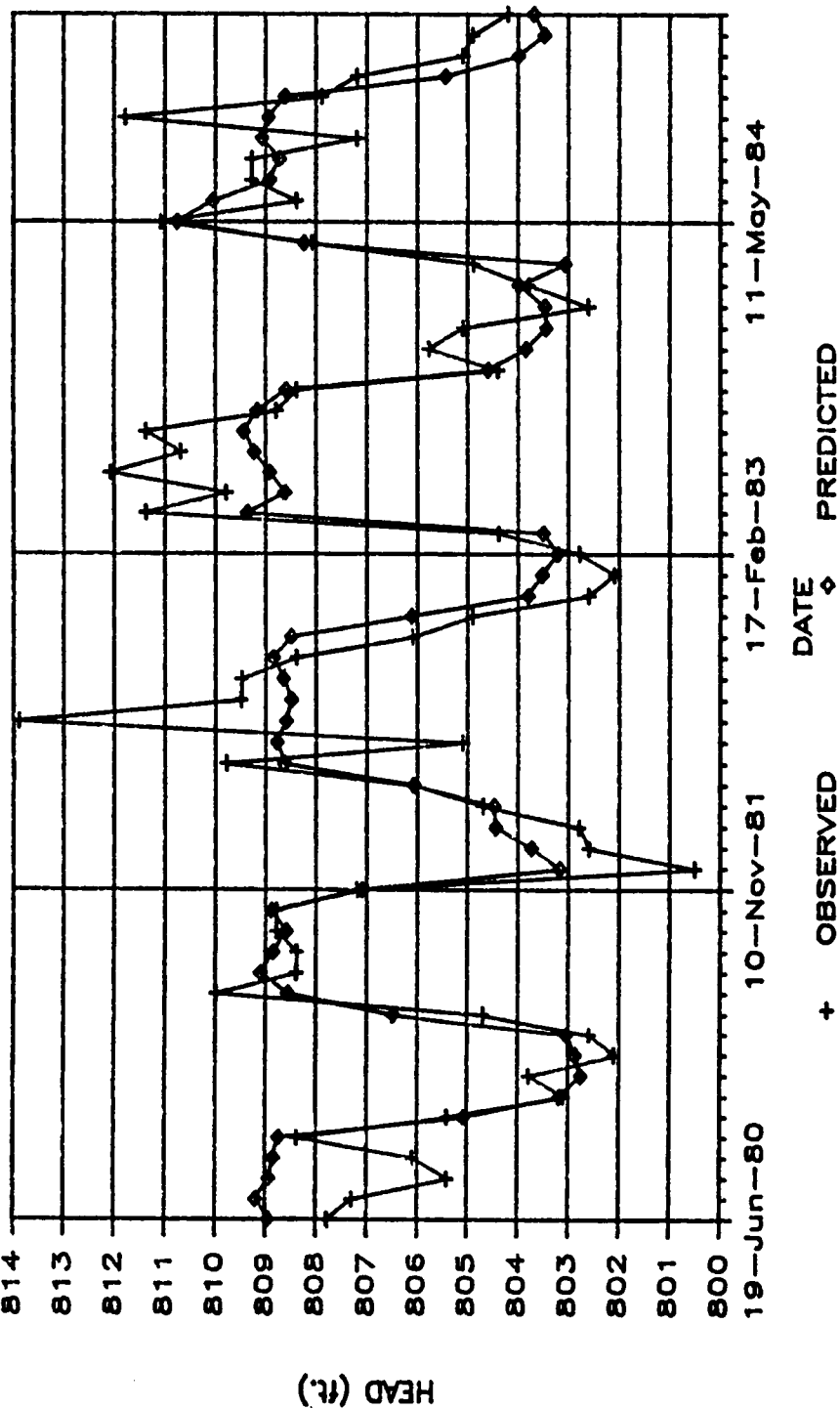


FIGURE A-24. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CU-2

# REGRESSION MODEL : PIEZOMETER CU-3

$CU-3 = -59.8 + 0.553 * HW10TO12 + .569 * TW10TO12$

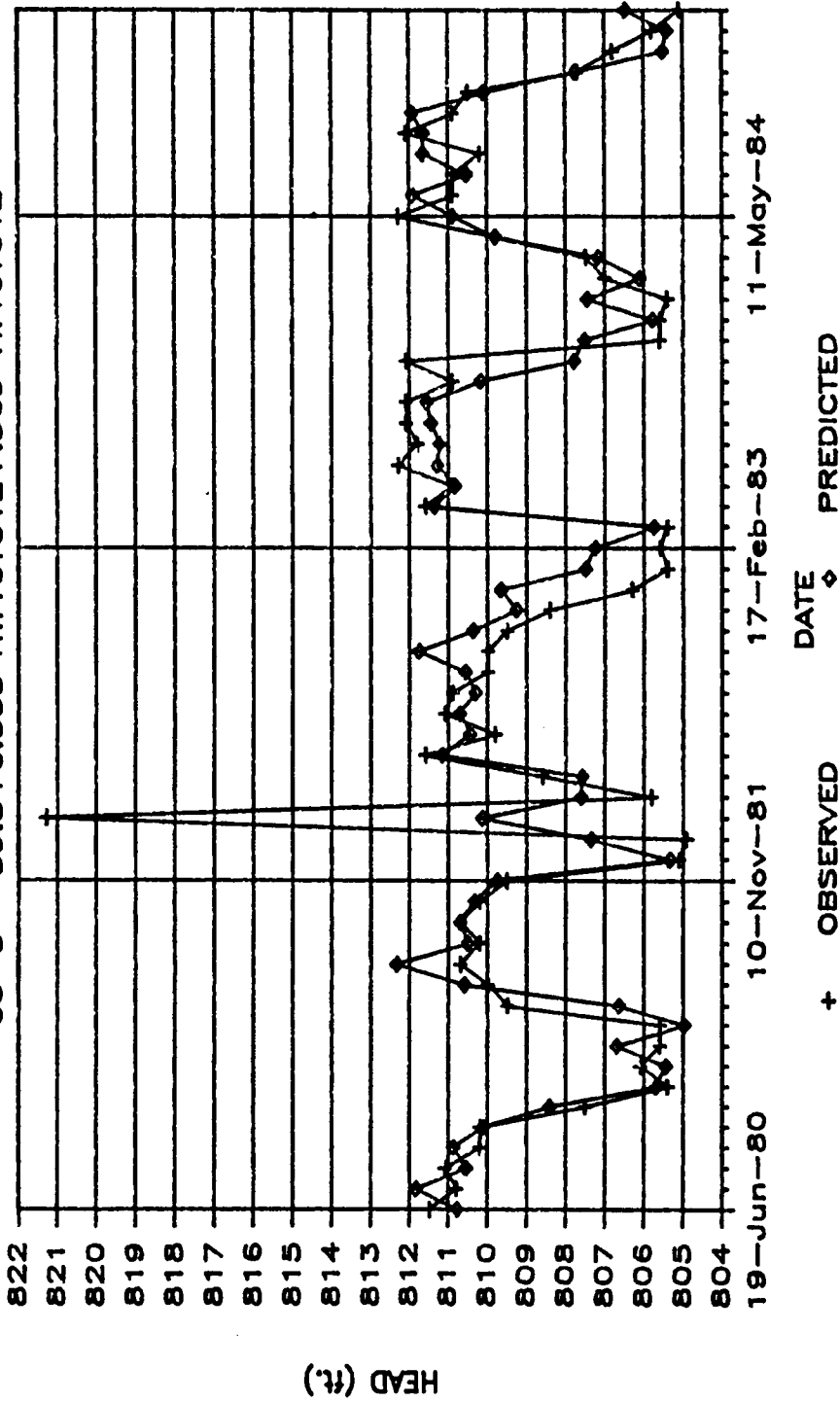


FIGURE A-25. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CU-3

# REGRESSION MODEL : PIEZOMETER CE

$$CE = 335.54 + 0.011 * HWAVG30 + 0.608 * TW10TO12$$

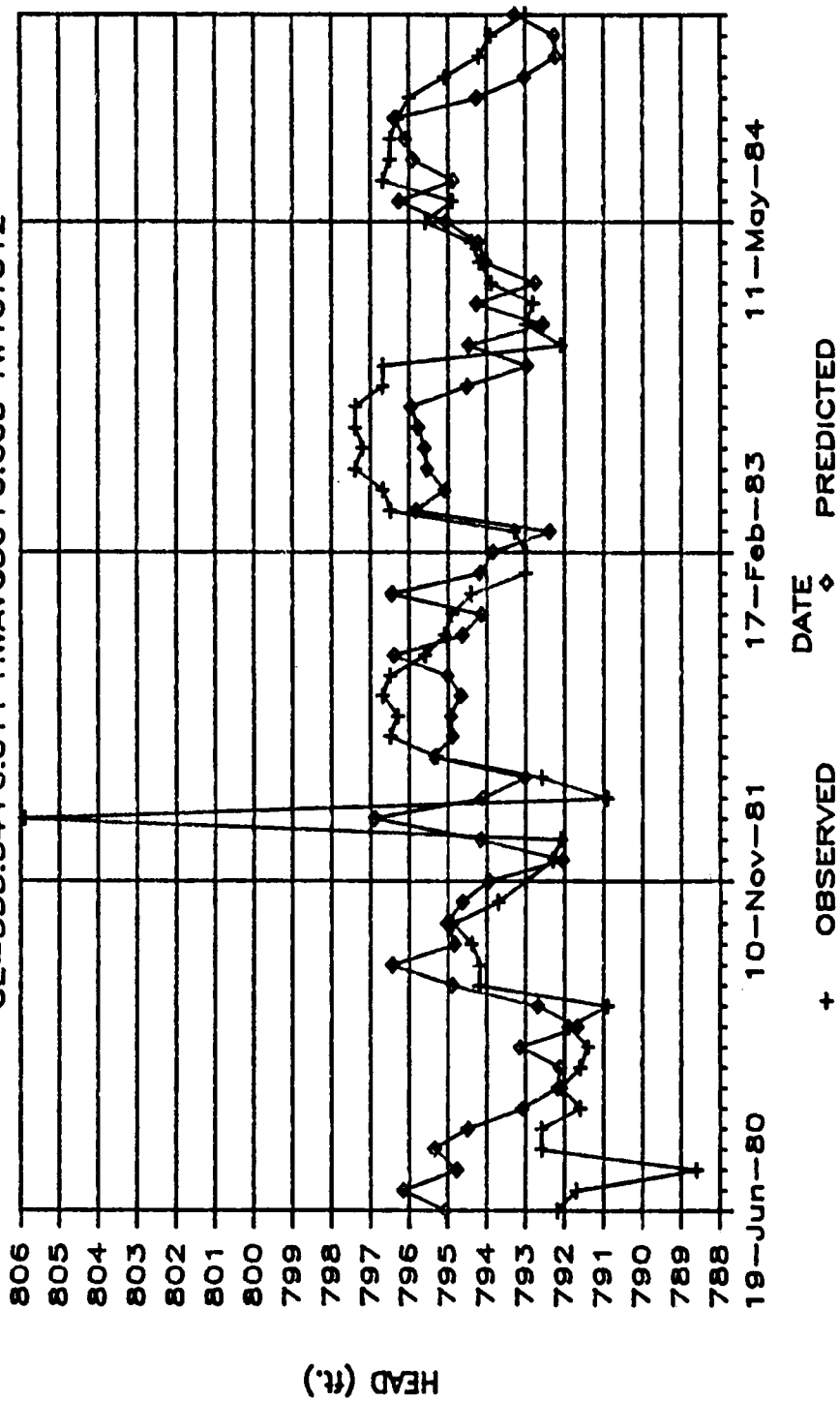


FIGURE A-26. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CE

# REGRESSION MODEL : PIEZOMETER CD-1

$$CD-1 = 7.37 + 0.349 * HWAVG10 + 0.609 * TWAVG30$$

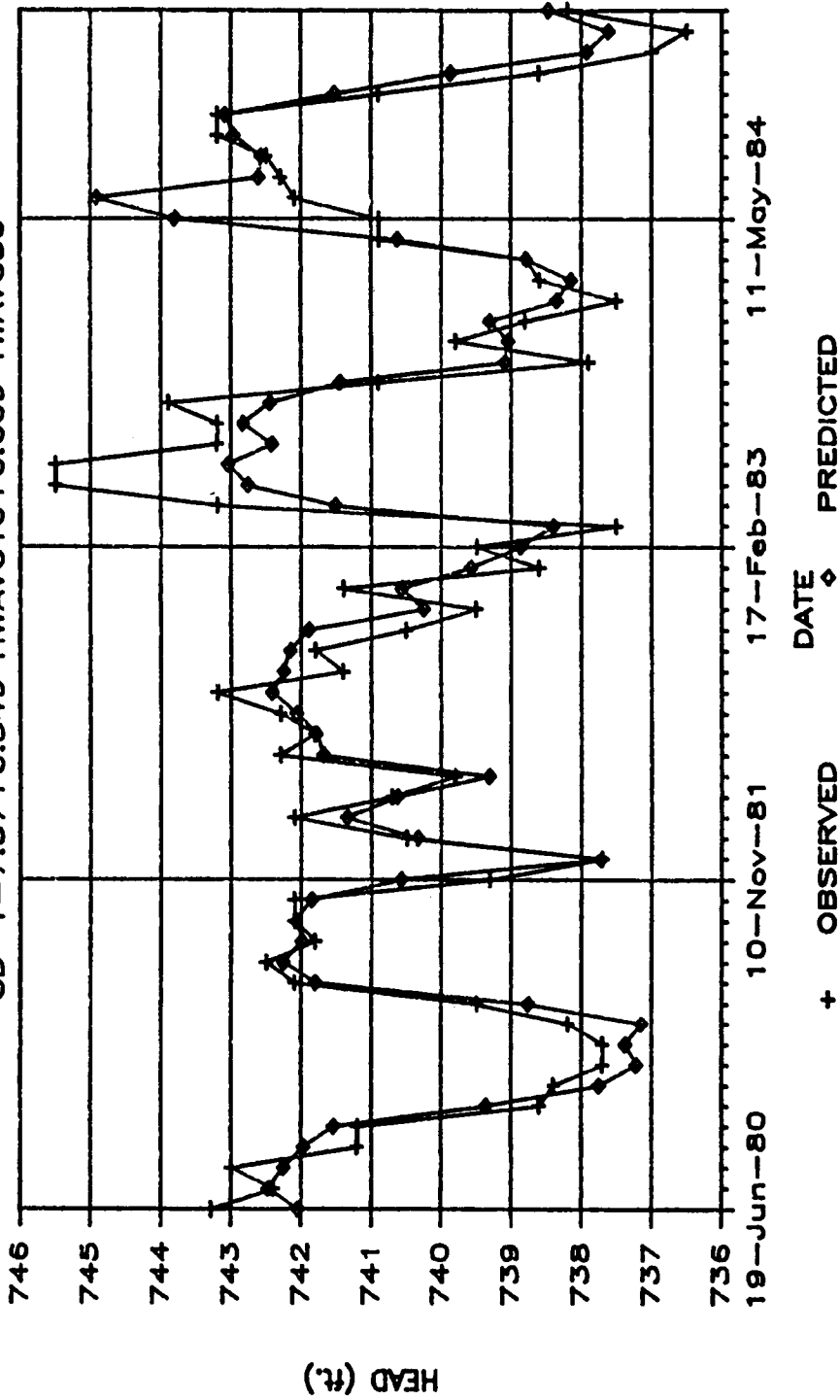


FIGURE A-27. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CD-1

REGRESSION MODEL : PIEZOMETER CD-2

$CD-2=43.54+0.280*HWAVG3+0.635*TWAVG3$

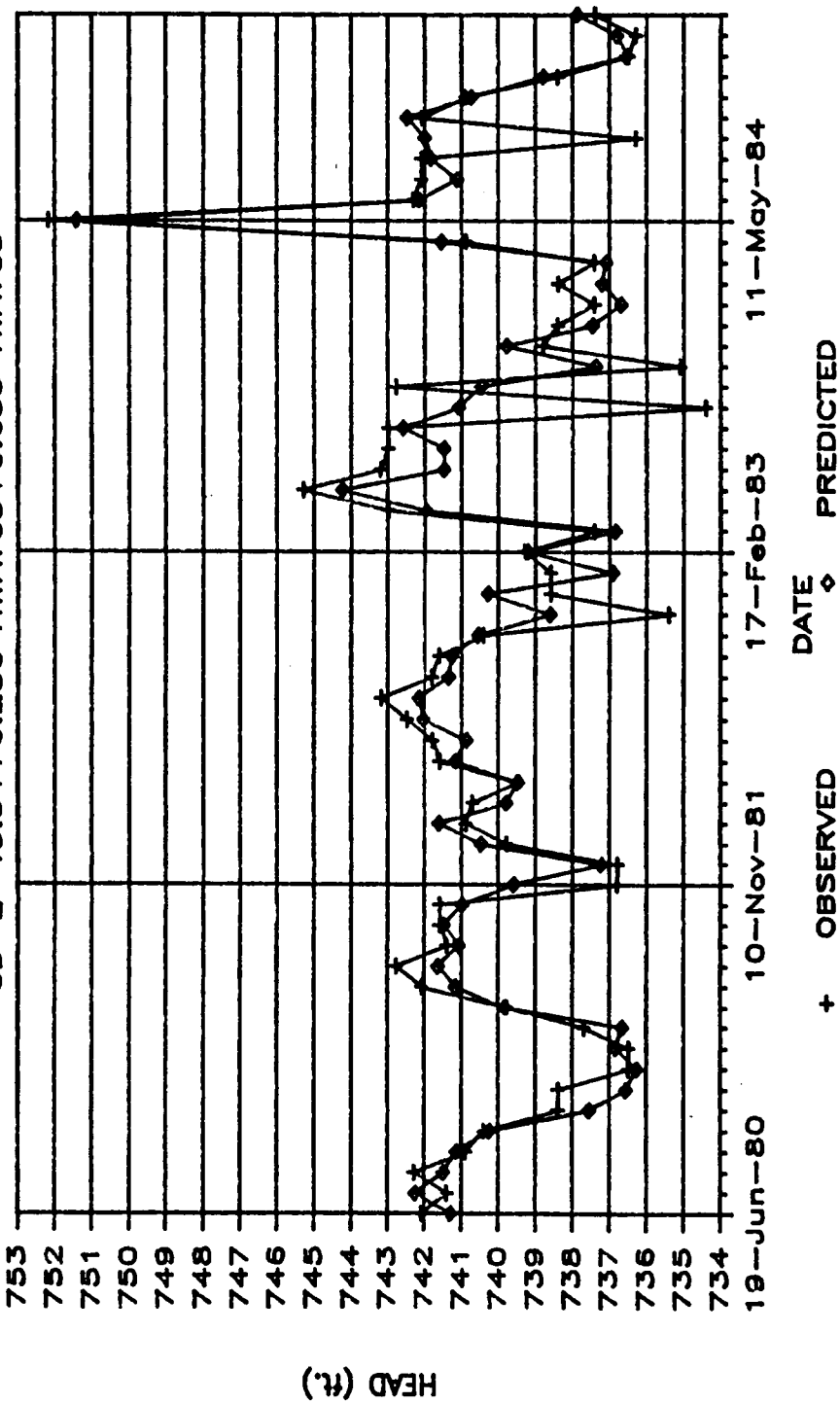


FIGURE A-28. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CD-2

# REGRESSION MODEL : PIEZOMETER CD-3

$$CD-3 = 173.26 + 0.160 * HWAVG3 + 0.592 * TWAVG3$$

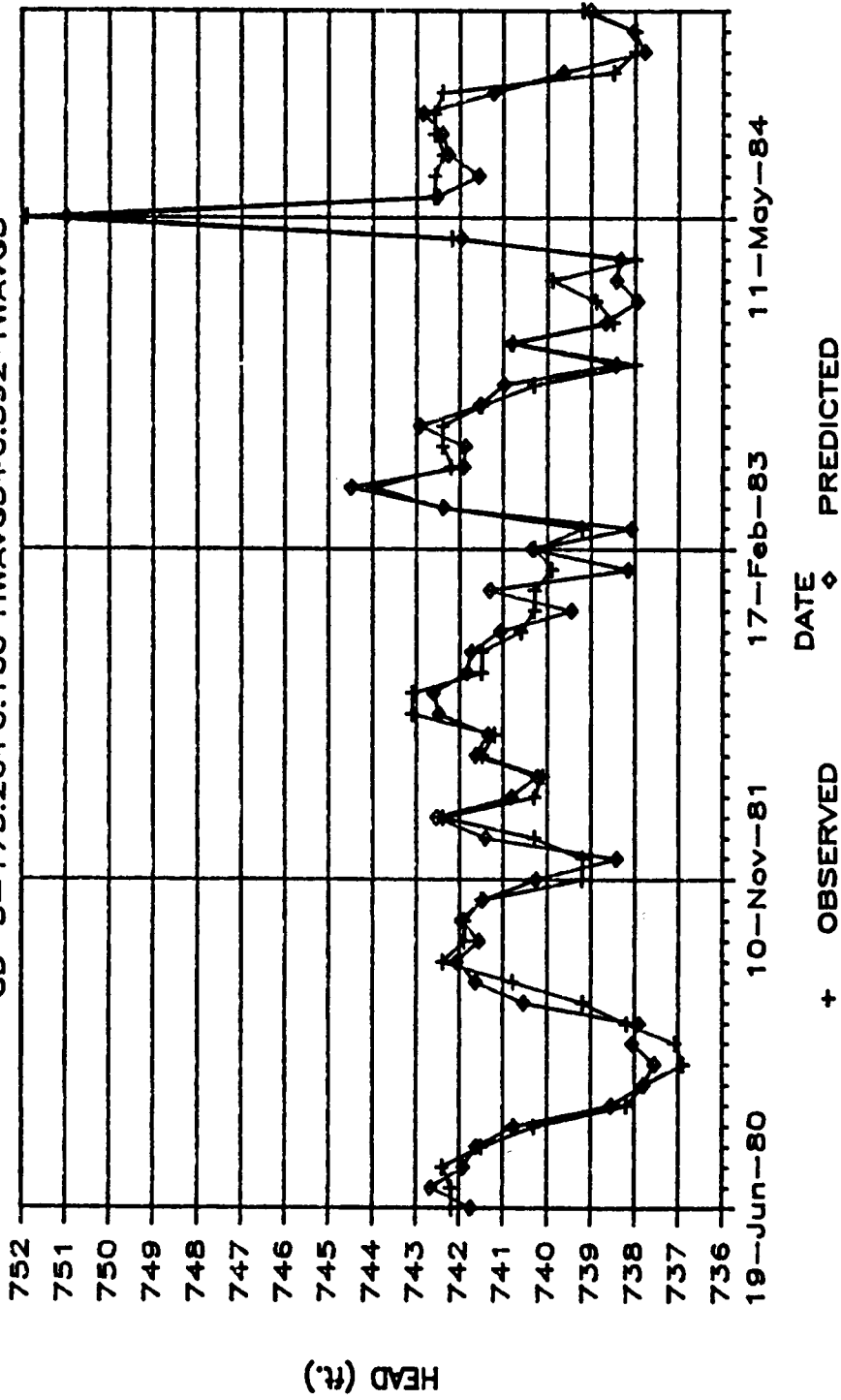


FIGURE A-29. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CD-3

# REGRESSION MODEL : PIEZOMETER CD-4

$$CD-4 = 73.49 + 0.275 * HWAVG3 + 0.599 * TWAVG3$$

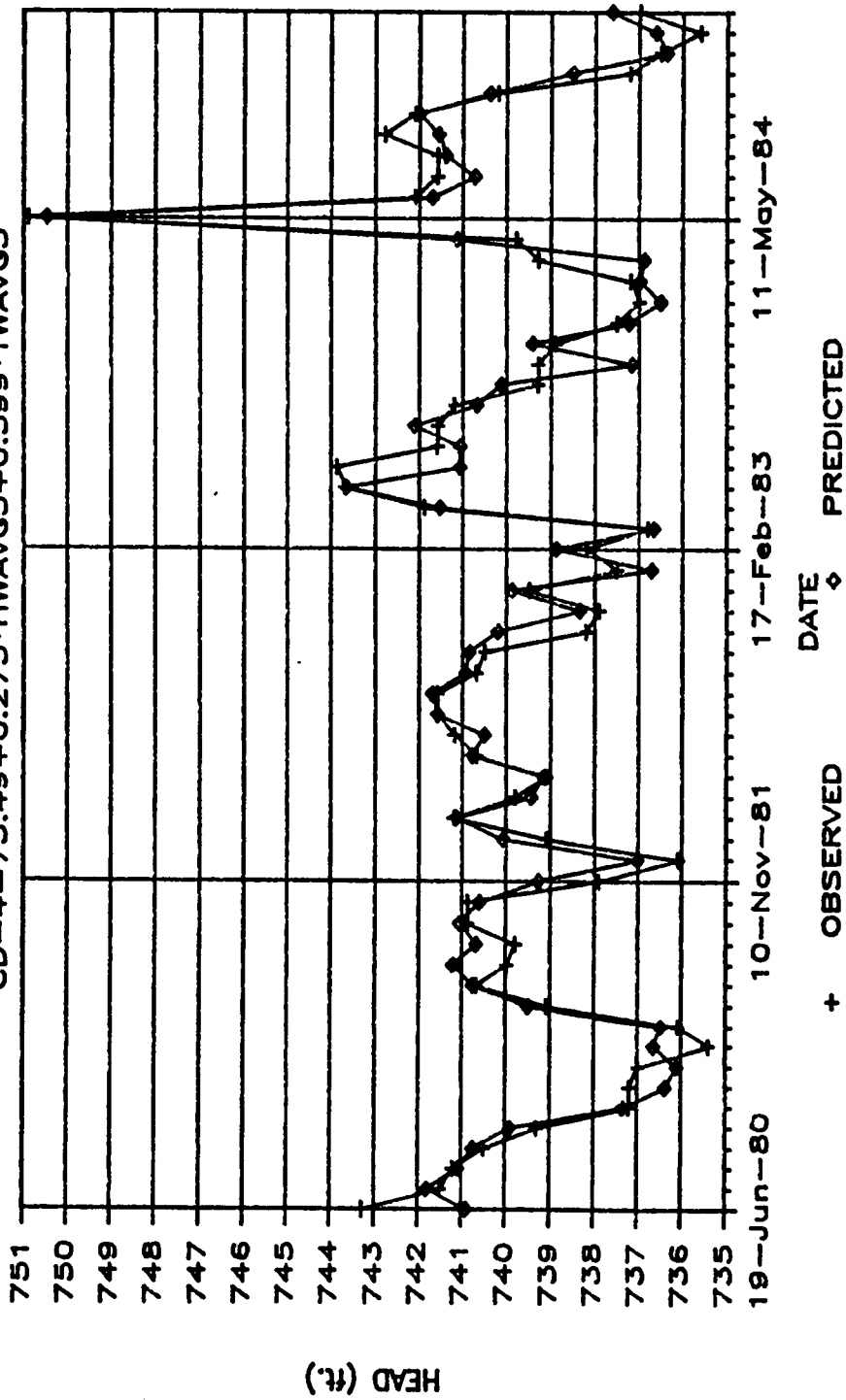


FIGURE A-30. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CD-4

# REGRESSION MODEL : PIEZOMETER CD-5

$$CD-5 = -7.54 + 0.390 * HWAVG3 + 0.581 * TWAVG5$$

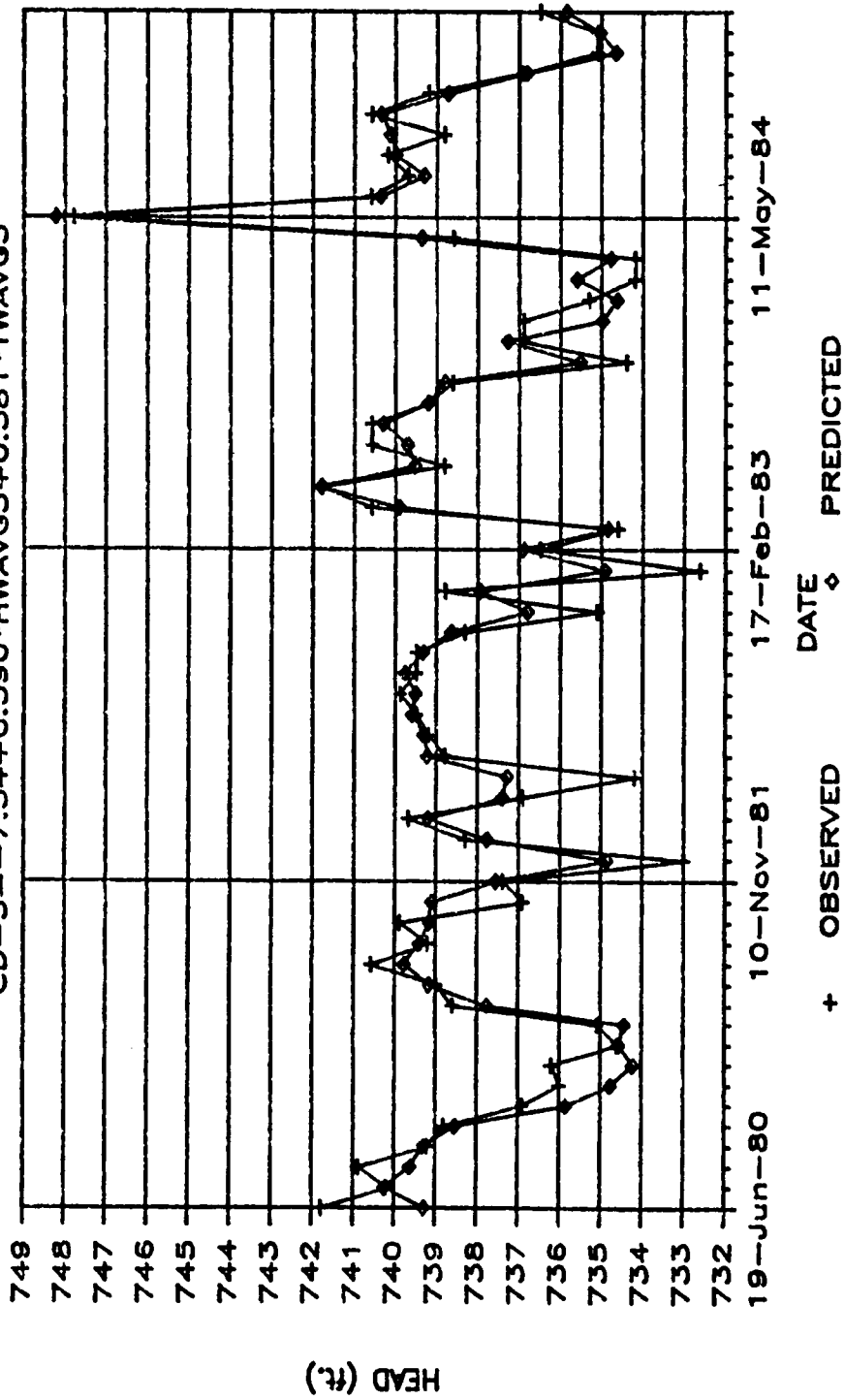


FIGURE A-31. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CD-5

# REGRESSION MODEL : PIEZOMETER CD-6

$$CD-6 = 1.03 + 0.2266 * HWAVG3 + 0.749 * TWAVG10$$

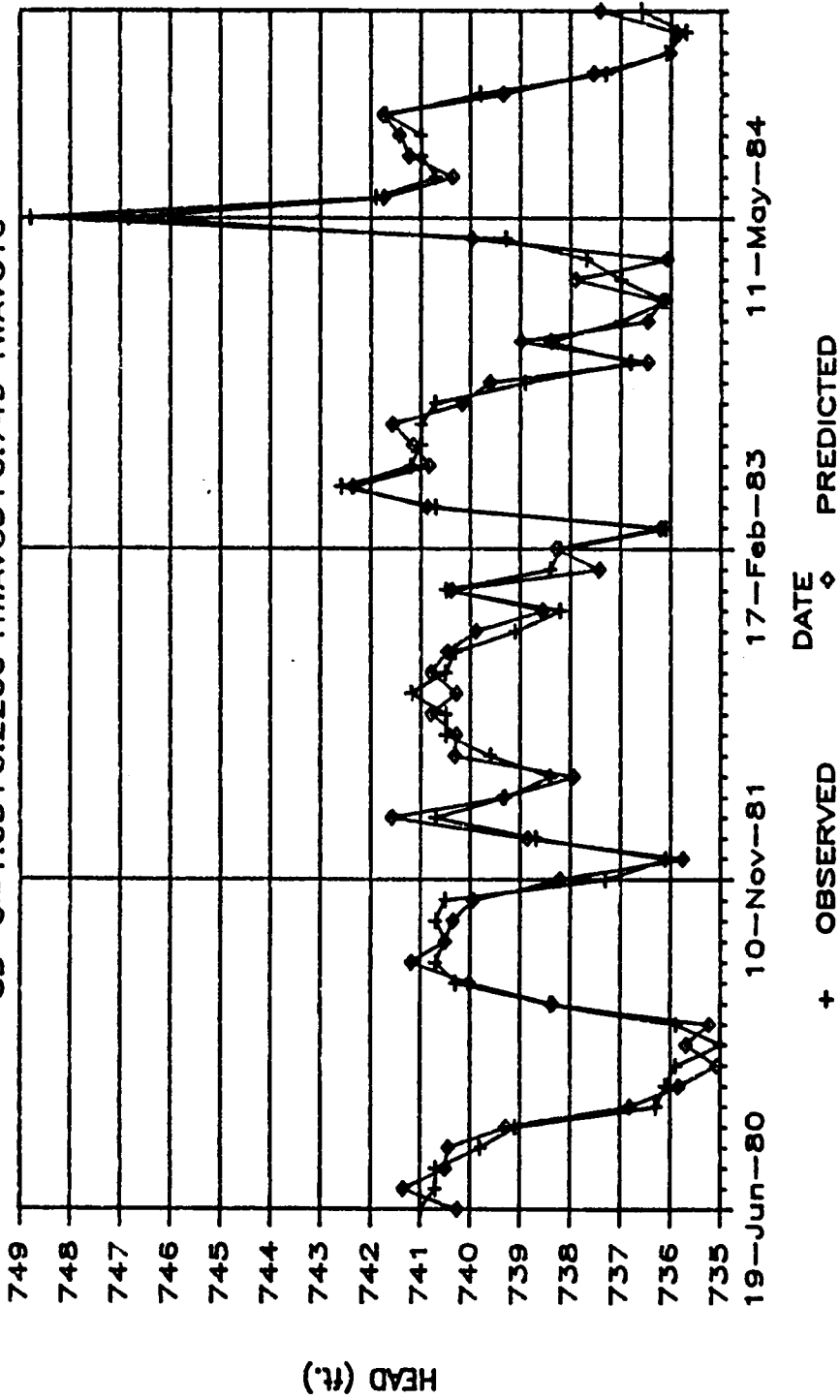


FIGURE A-32. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER CD-6

# REGRESSION MODEL : PIEZOMETER DU-1

DU-1 = -92.68 + 1.152\*HW - 0.054\*TWAVG30

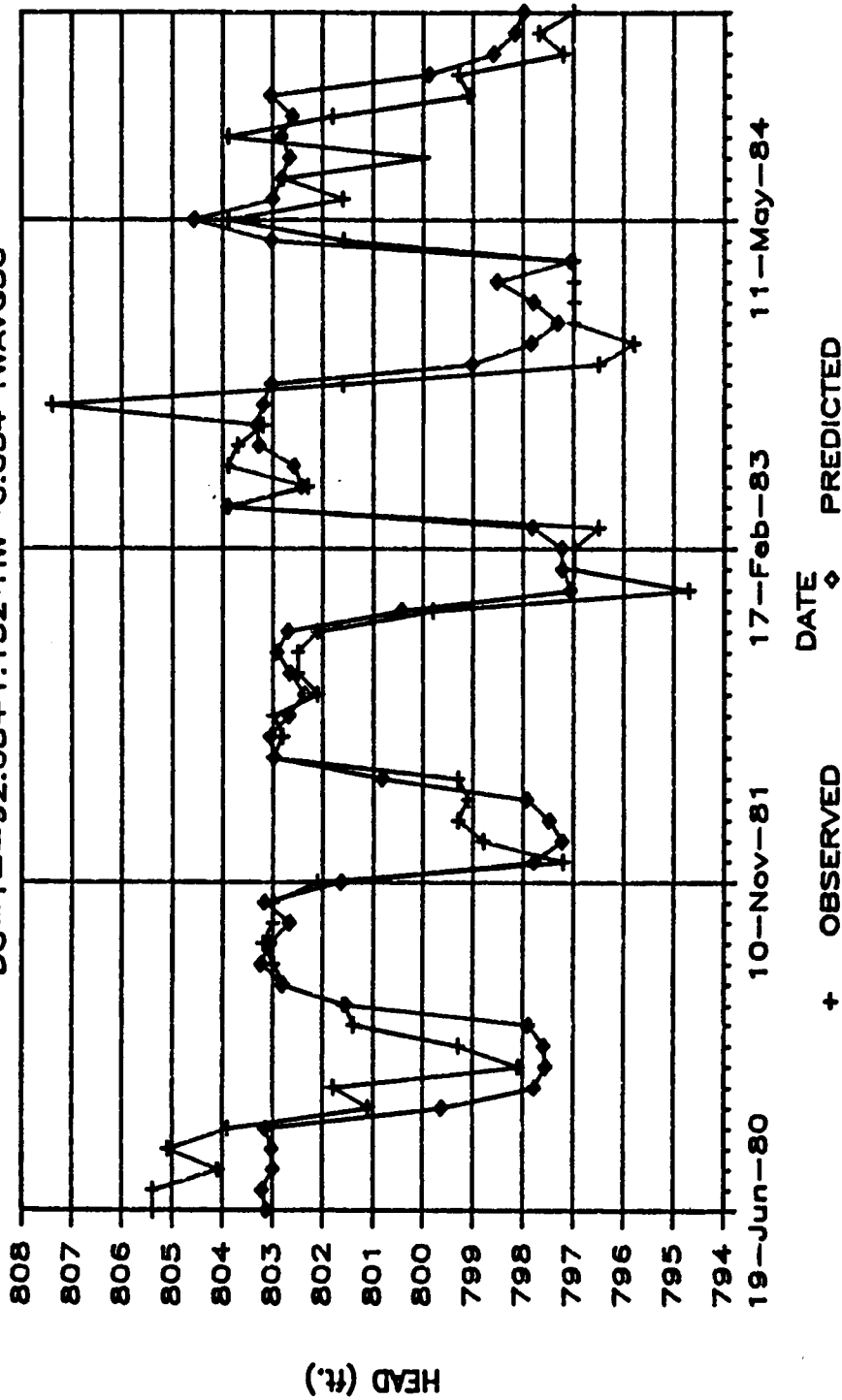


FIGURE A-33. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER DU-1

# REGRESSION MODEL : PIEZOMETER DU-2

$DU-2 = -56.81 + 1.040 \cdot HW + 0.025 \cdot TWAVG3$

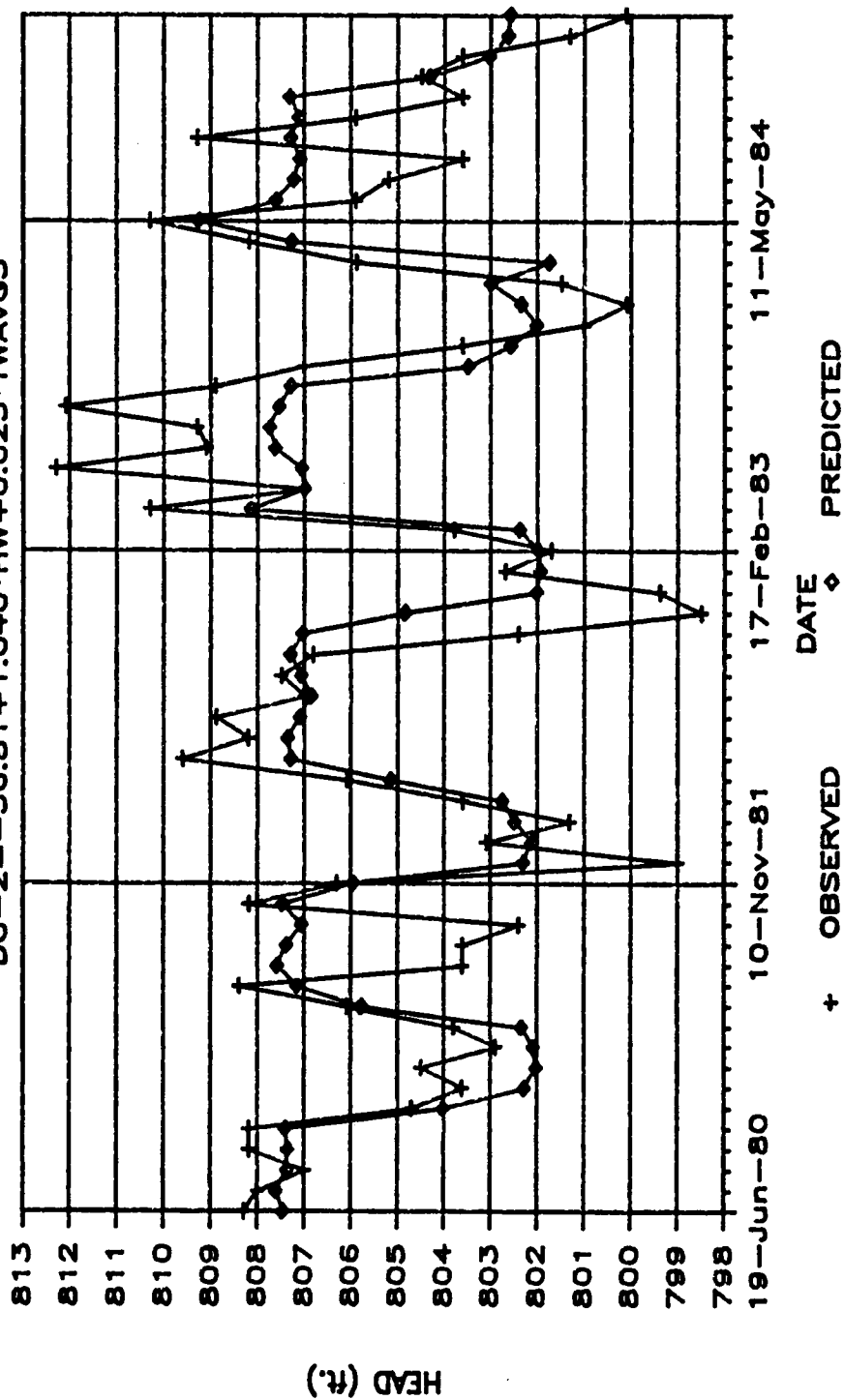


FIGURE A-34. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER DU-2

# REGRESSION MODEL : PIEZOMETER DD-1

$$DD-1 = 56.47 + 0.335 * HWAVG3 + 0.558 * TWAVG3$$

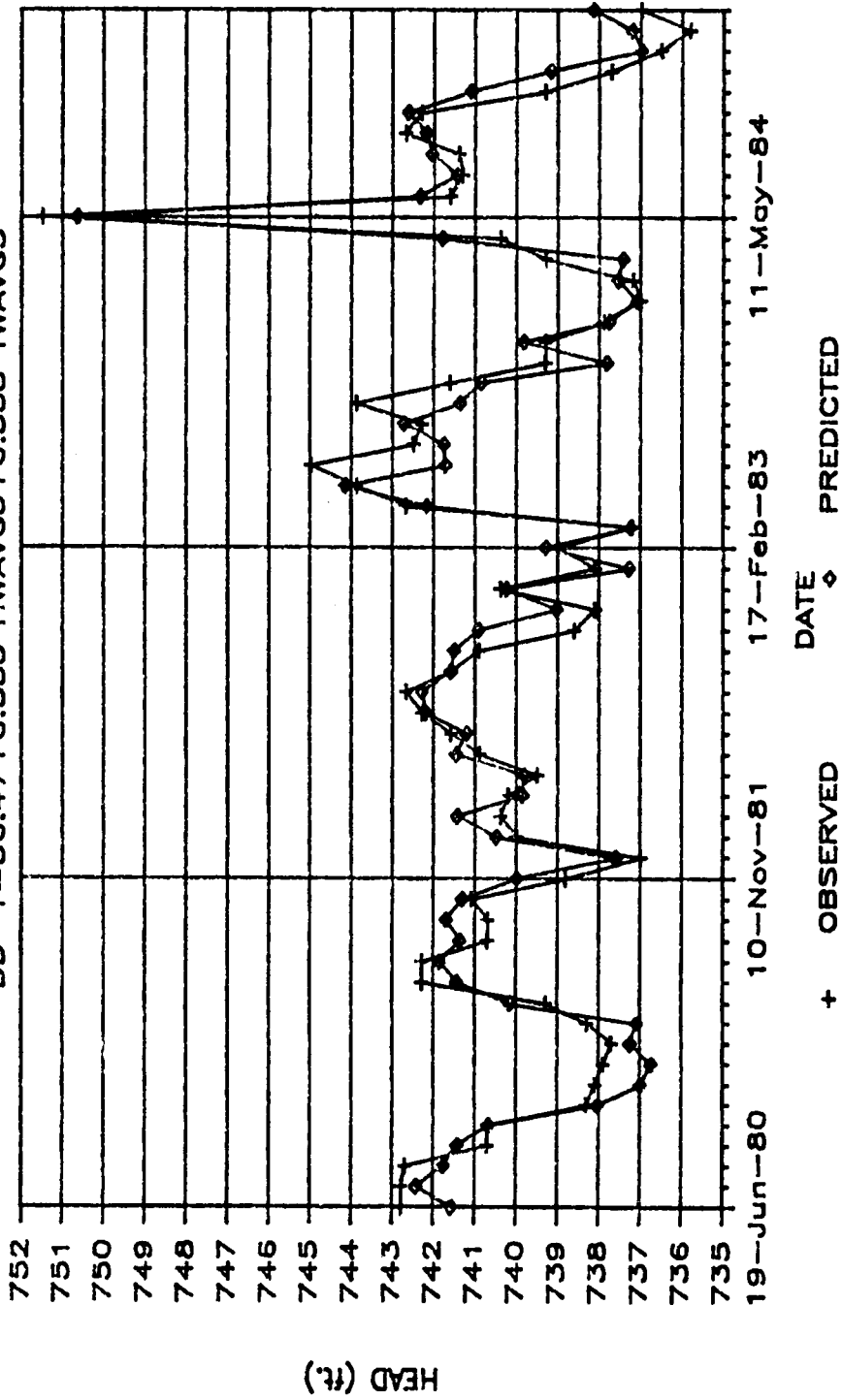


FIGURE A-35. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER DD-1

# REGRESSION MODEL : PIEZOMETER DD-2

$$DD-2 = 92.75 + 0.225 * HWAVG3 + 0.627 * TWAVG3$$

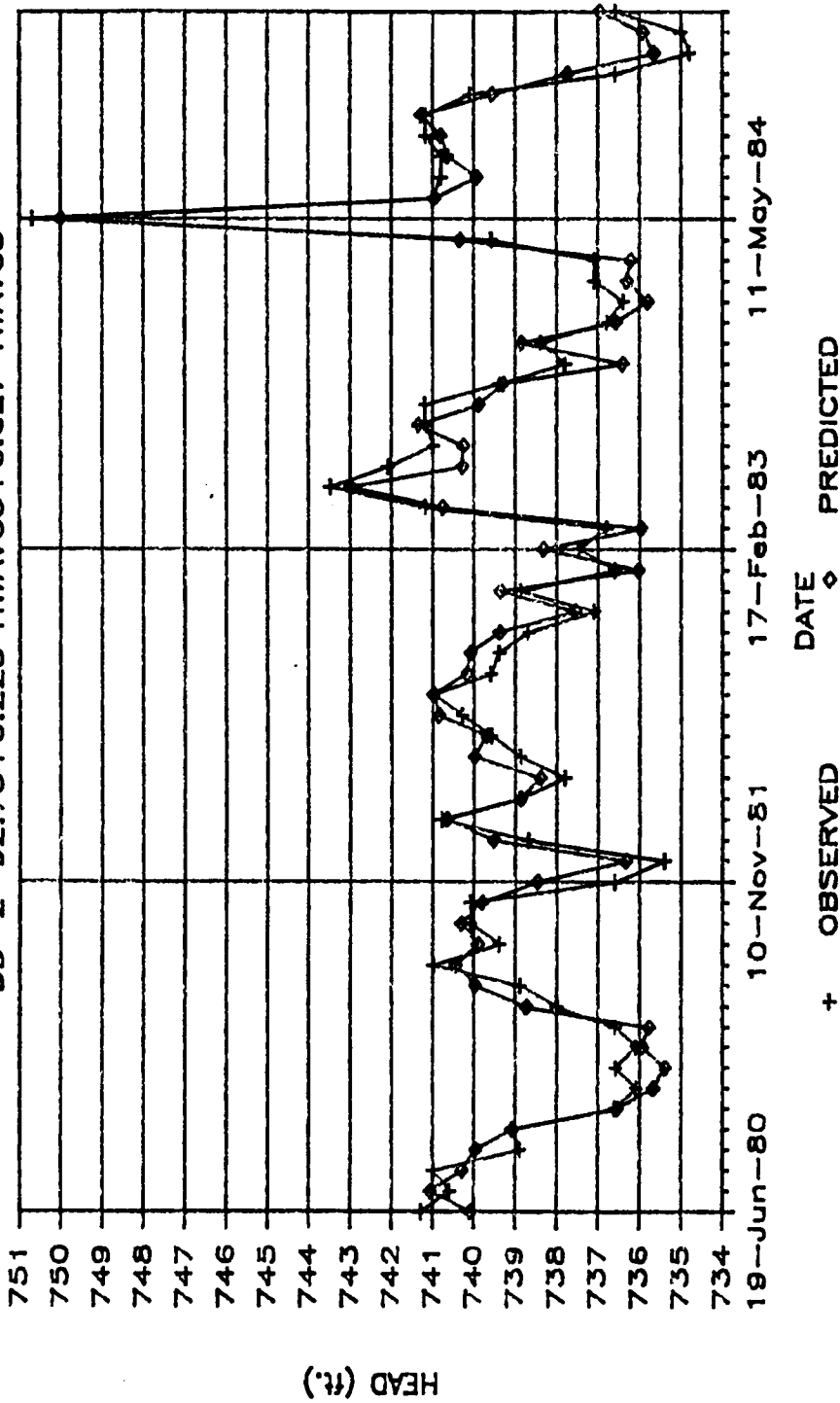


FIGURE A-36. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER DD-2

# REGRESSION MODEL : PIEZOMETER DD-4

$$DD-4 = 37.59 + 0.333 \cdot HWAVG3 + 0.582 \cdot TWAVG5$$

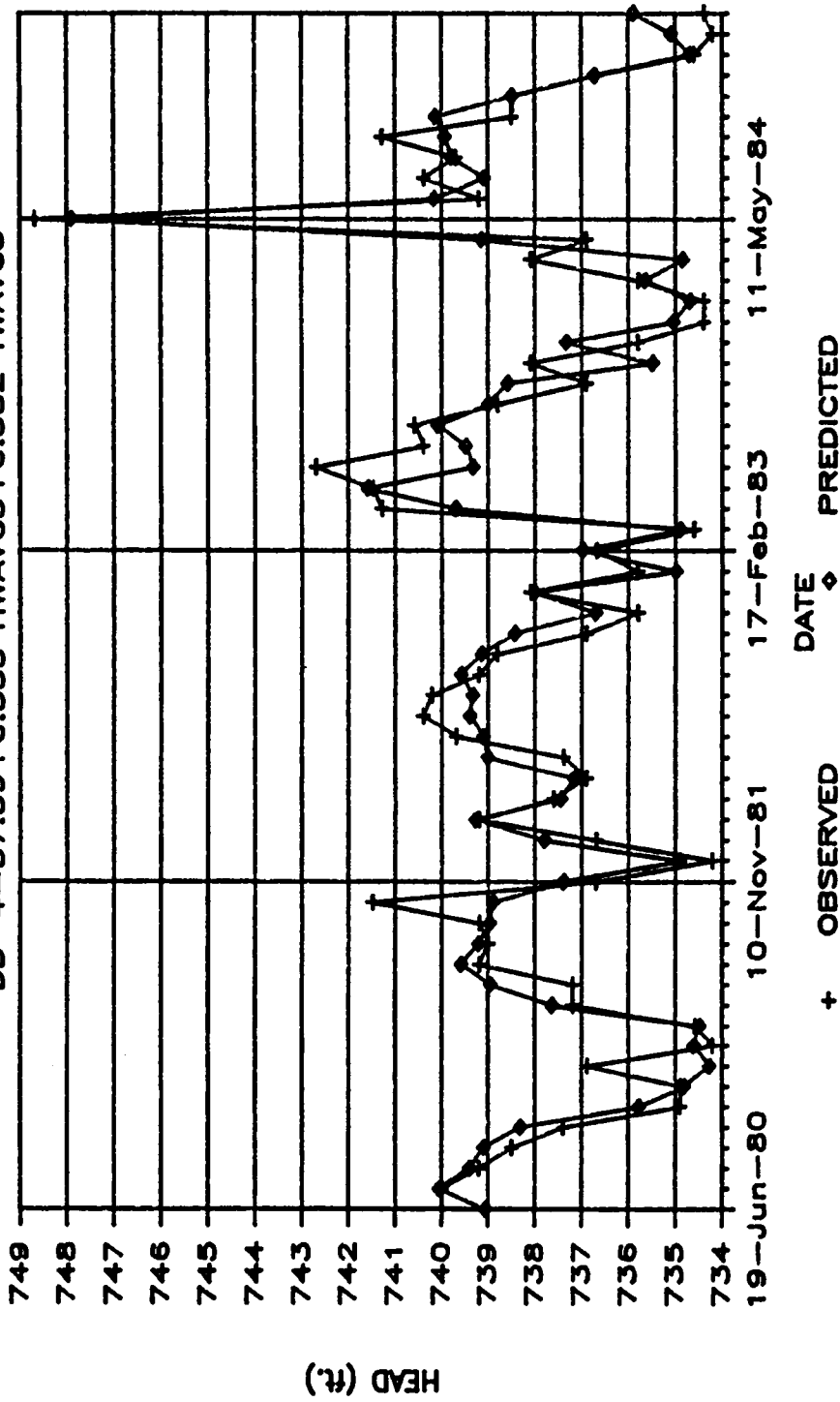


FIGURE A-37. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER DD-4

# REGRESSION MODEL : PIEZOMETER DD-5

$$DD-5 = -283.2 + 0.67 \cdot HW10TO12 + 0.642 \cdot TWAVG10$$

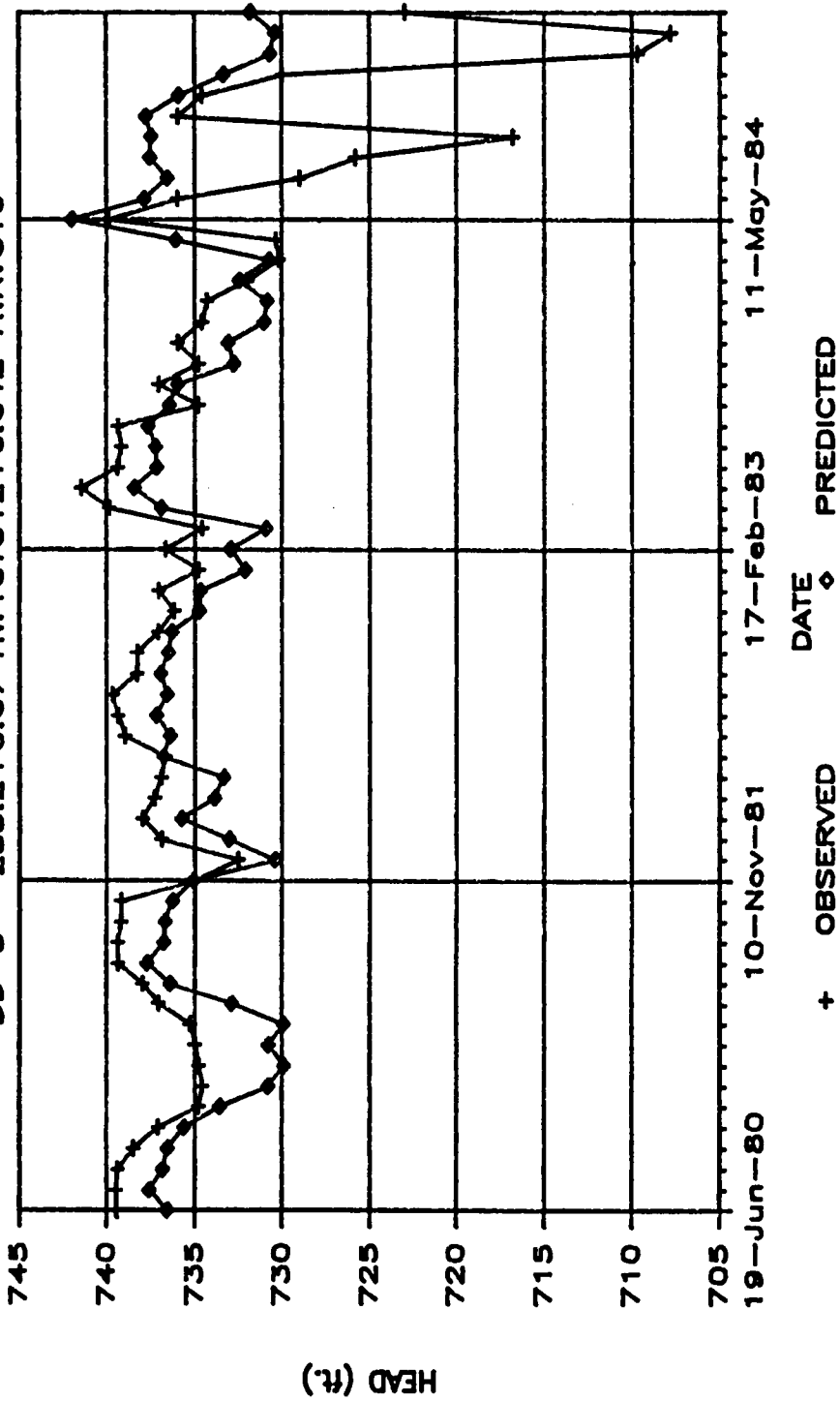


FIGURE A-38. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER DD-5

# REGRESSION MODEL : PIEZOMETER EU-1

EU-1 =  $73.81 + 0.832 \cdot HW + 0.078 \cdot TWAVG30$

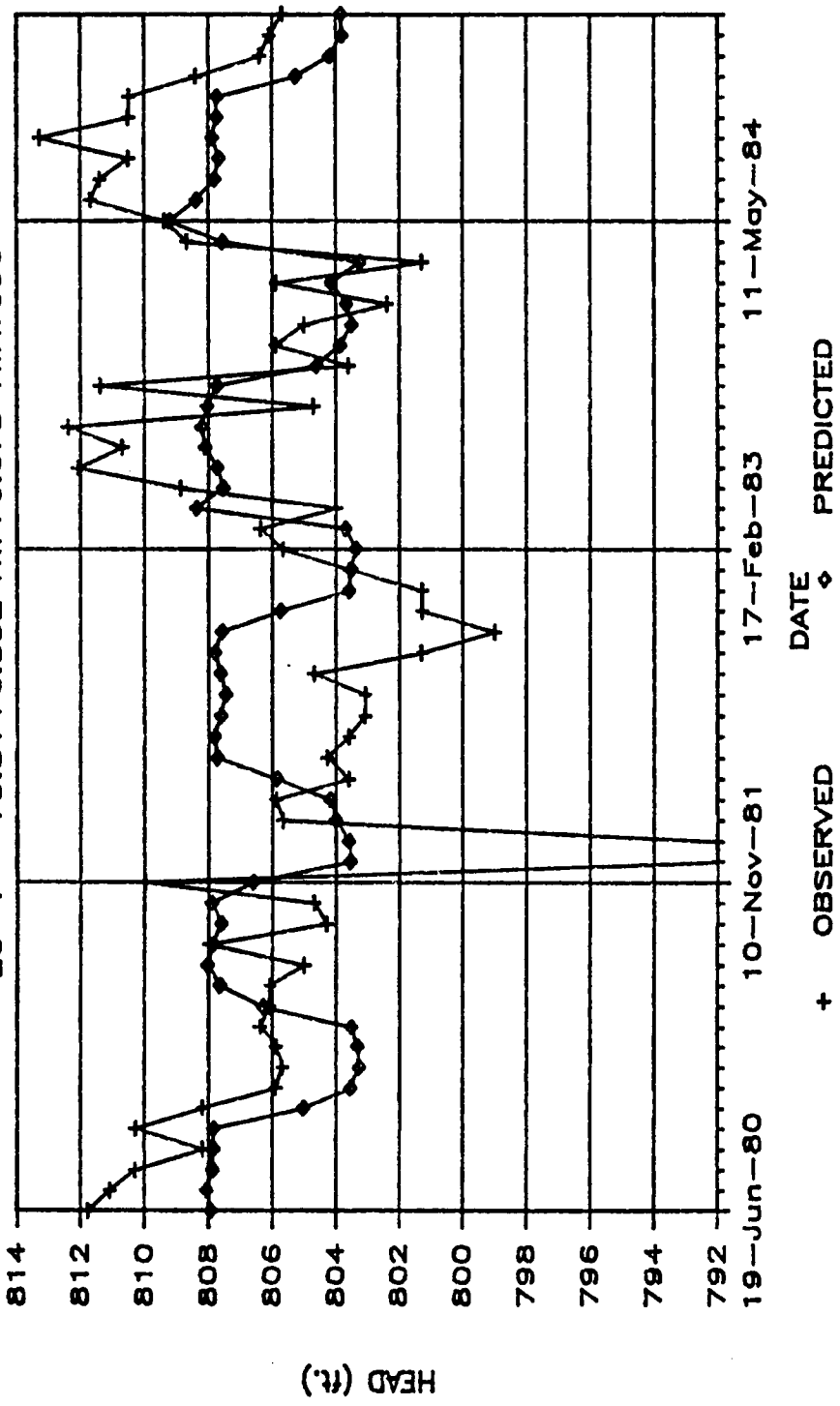


FIGURE A-39. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER EU-1

# REGRESSION MODEL : PIEZOMETER EU-2

EU-2 = -6.28\*1.029\*HWAVG3 - 0.026\*TWAVG30

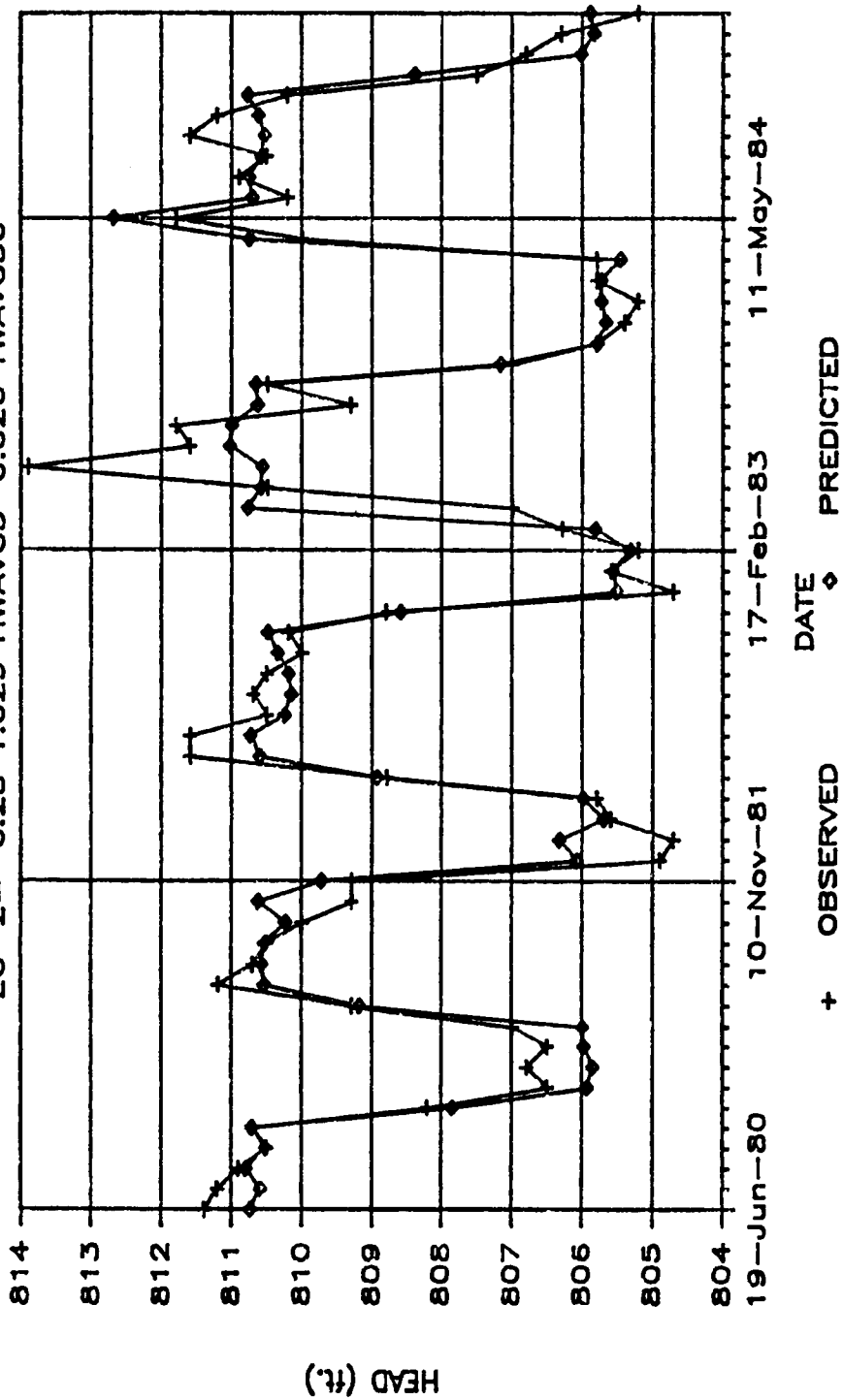


FIGURE A-40. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER EU-2

REGRESSION MODEL : PIEZOMETER EU-3

$$EU-3 = -39.55 + 1.044 * HW + 0.004 * TWAVG30$$

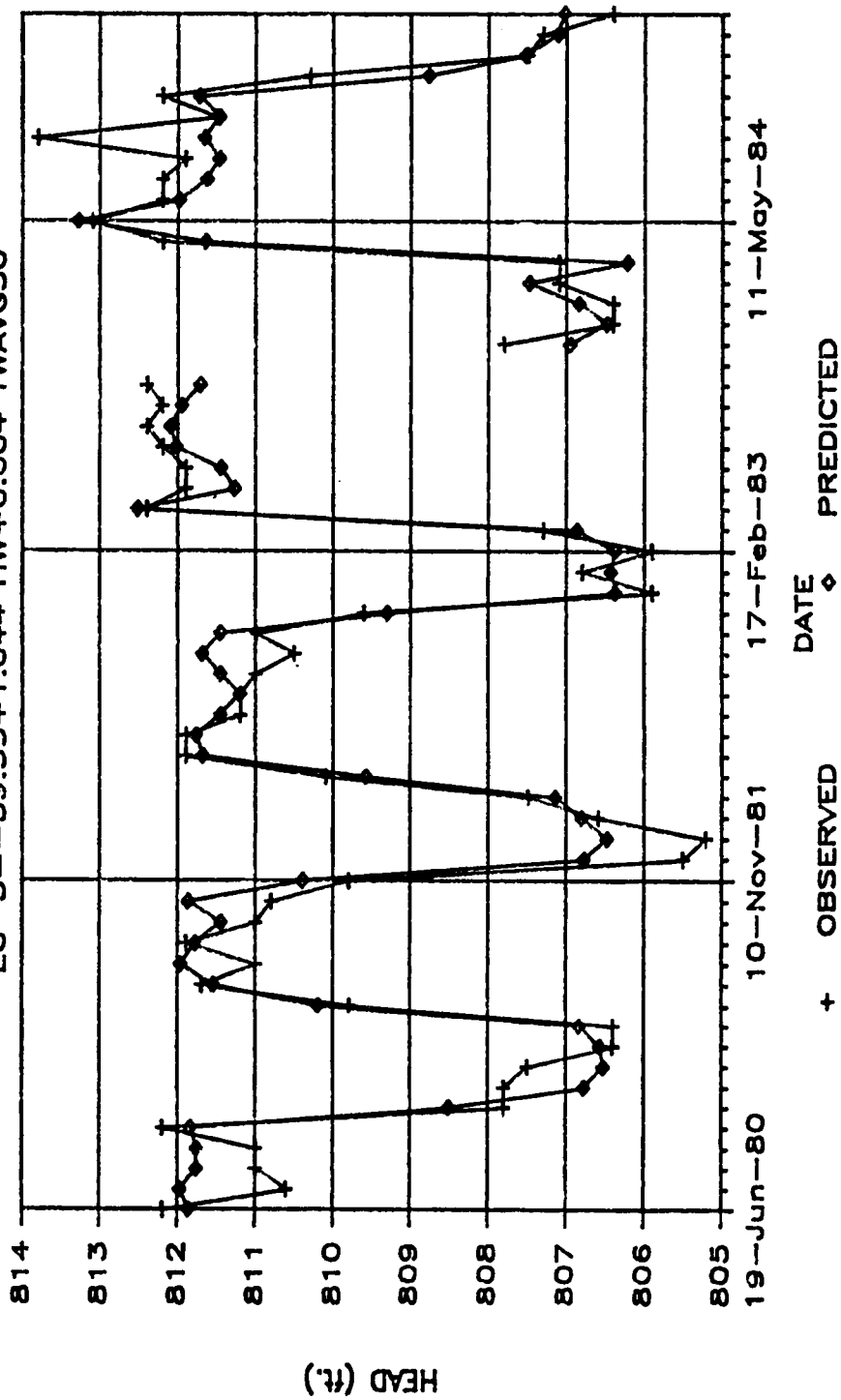


FIGURE A-41. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER EU-3

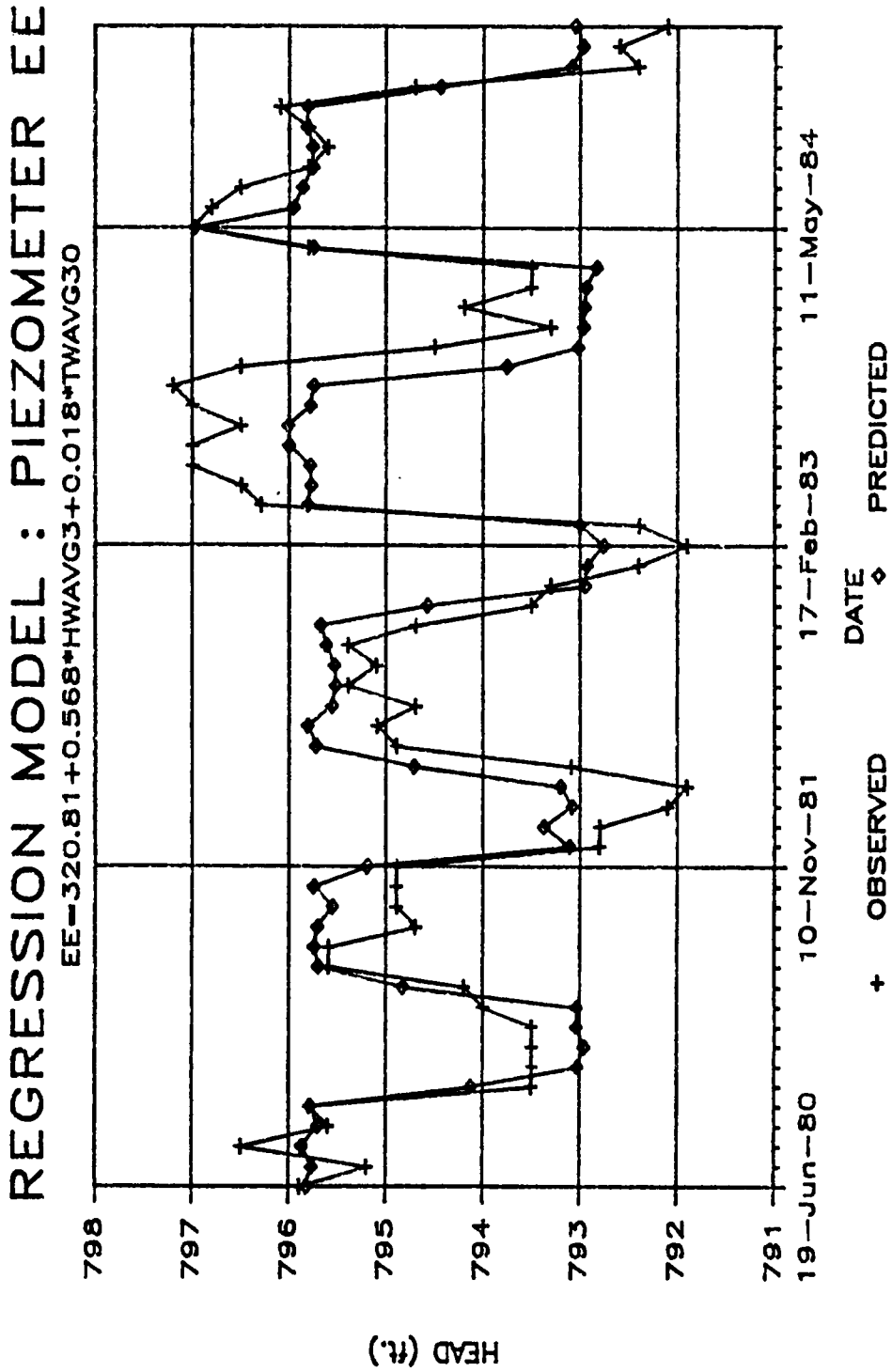


FIGURE A-42. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER EE

# REGRESSION MODEL : PIEZOMETER ED-1

$$ED-1 = 48.06 + 0.215 * HWAVG3 + 0.705 * TWAVG10$$

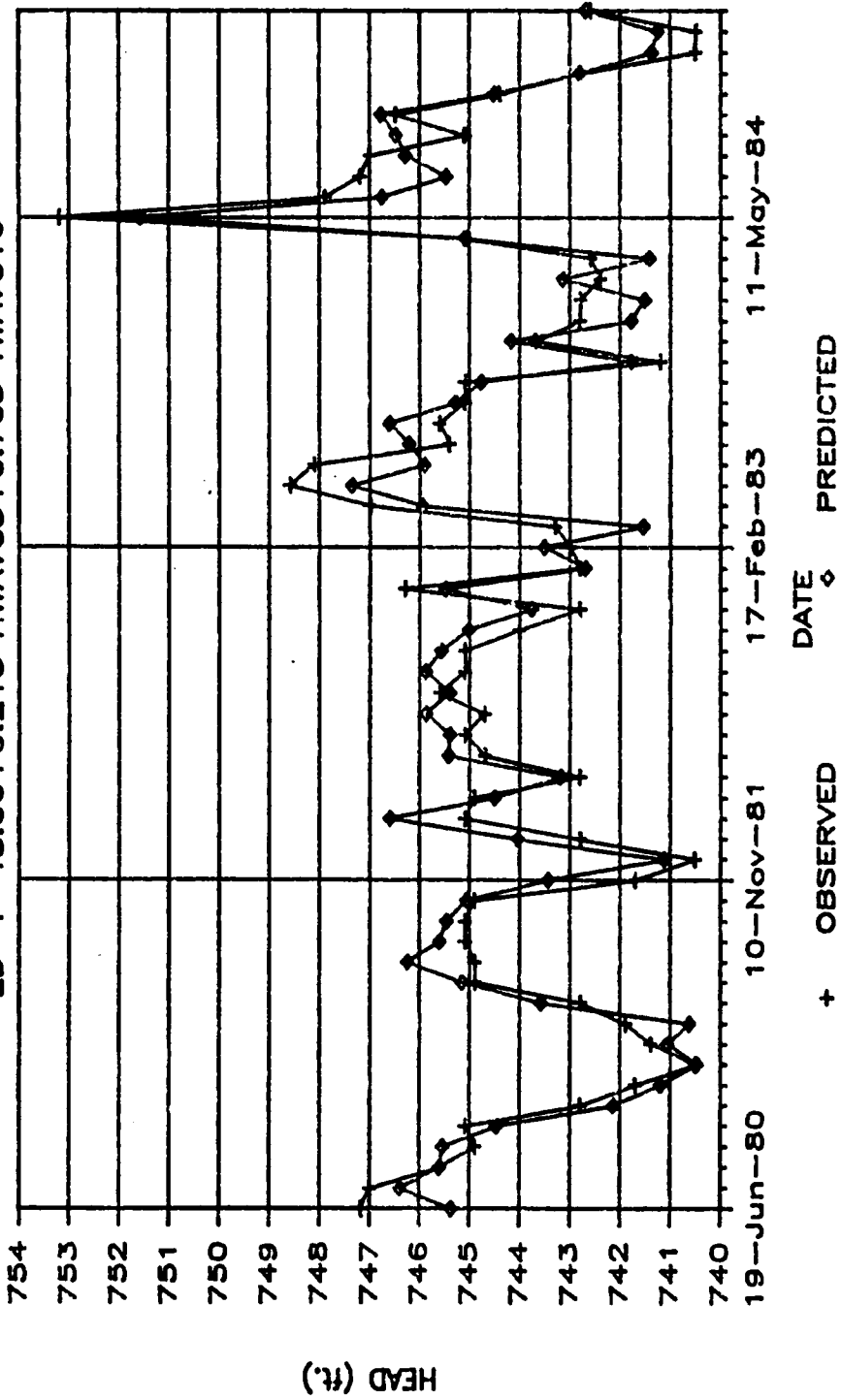


FIGURE A-43. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER ED-1

# REGRESSION MODEL : PIEZOMETER ED-2

$$ED-2 = 194.38 + 0.667 \cdot HW + 0.069 \cdot TWAVG30$$

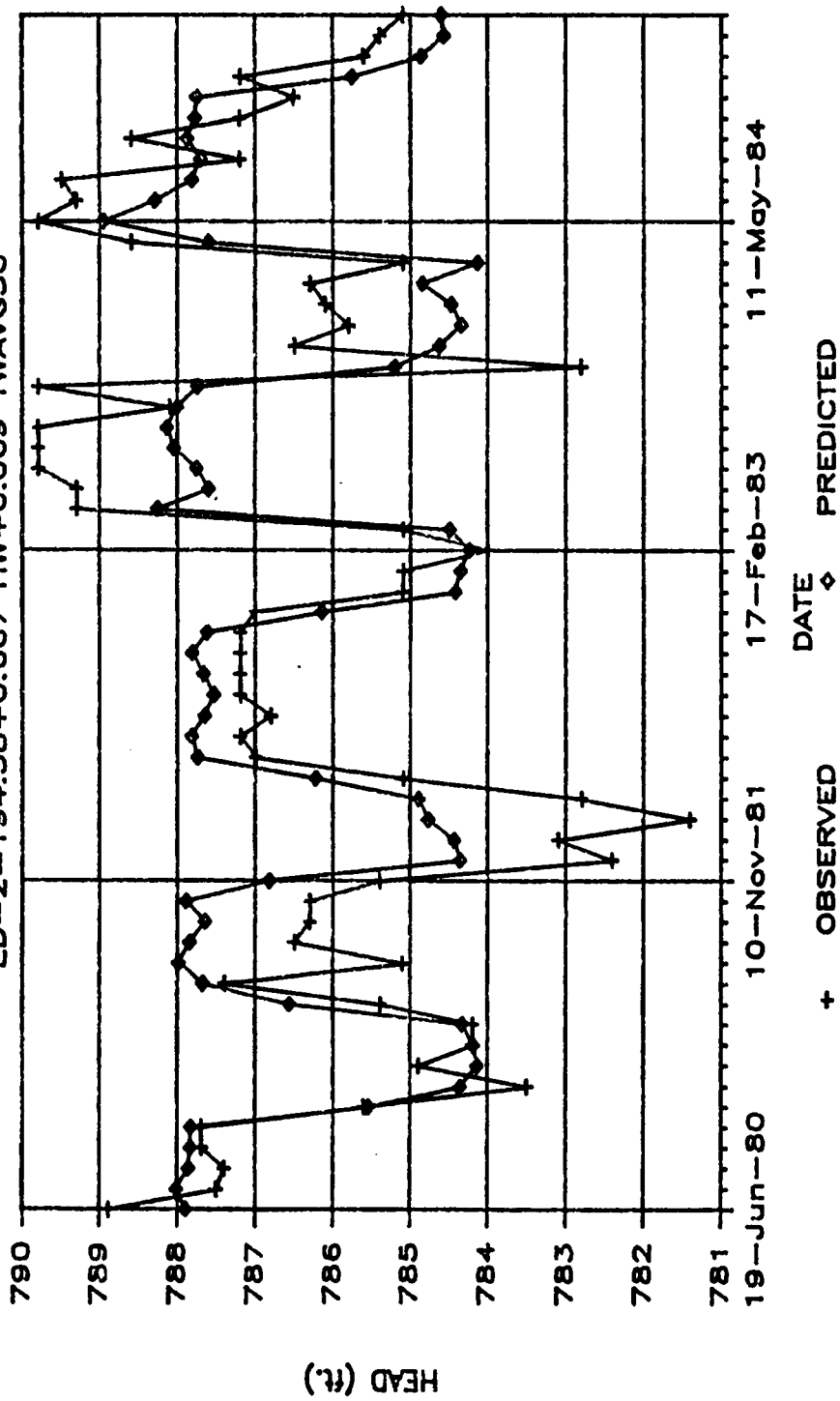


FIGURE A-44. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER ED-2

# REGRESSION MODEL : PIEZOMETER ED-3

$$ED-3 = 274.41 + 0.479 \cdot HWAVG3 + 0.172 \cdot TWAVG30$$

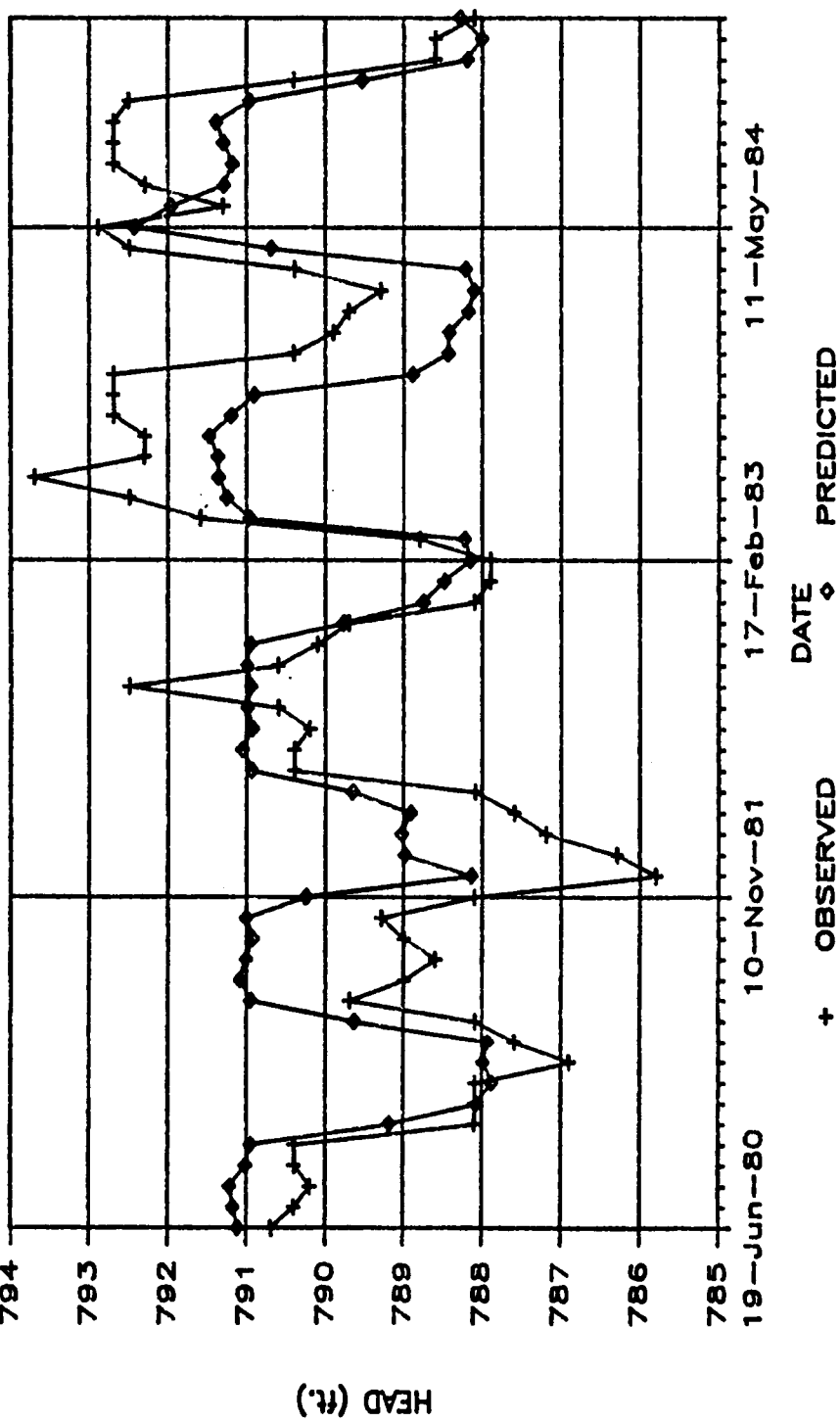


FIGURE A-45. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER ED-3

# REGRESSION MODEL : PIEZOMETER ED-4

$$ED-4 = 360.33 + 0.106 * HWAVG5 + 0.398 * TWAVG3$$

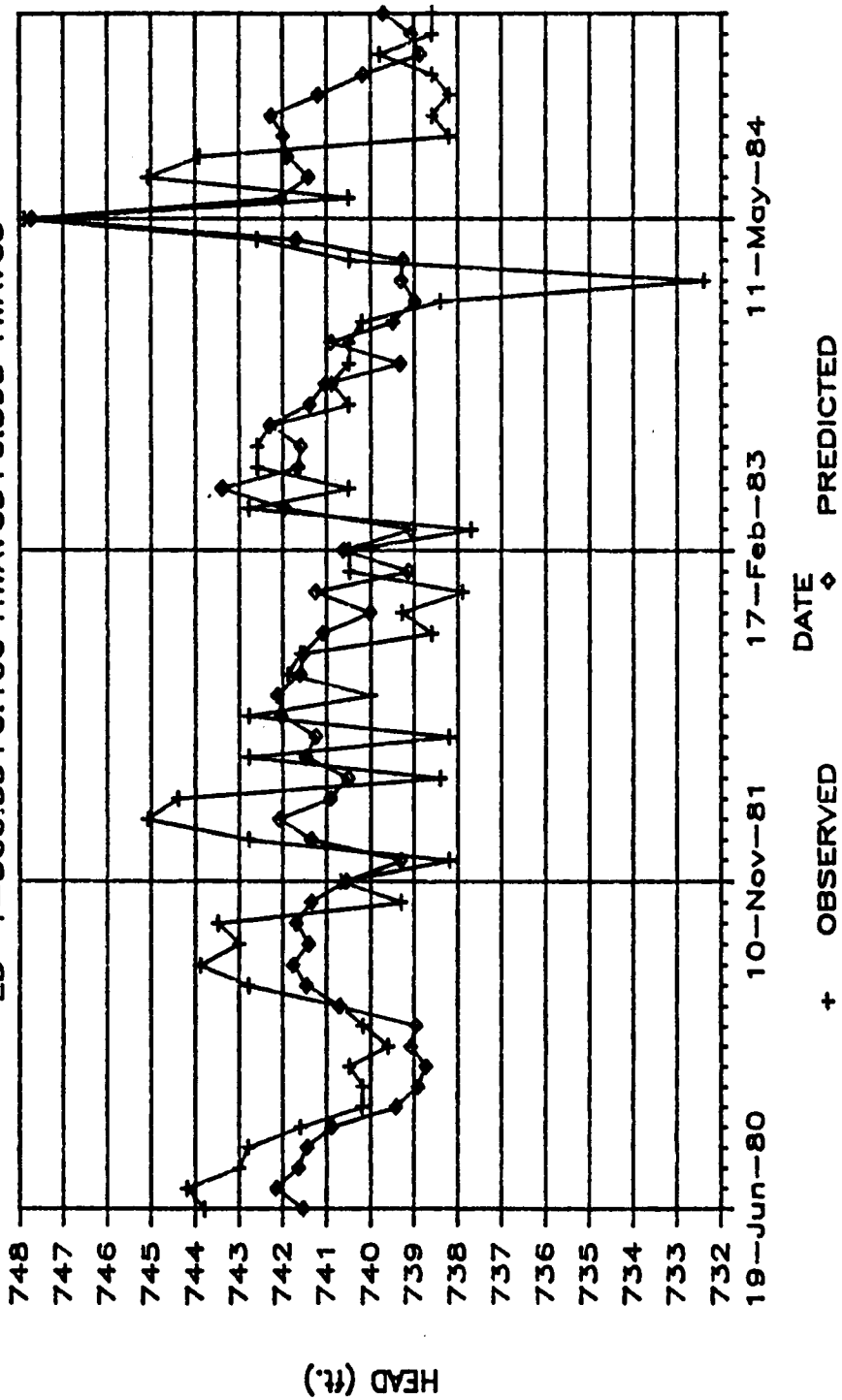


FIGURE A-46. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER ED-4

# REGRESSION MODEL : PIEZOMETER ED-5

$$ED-5 = 63.53 + 0.137 \cdot HWAVG3 + 0.768 \cdot TW4TO6$$

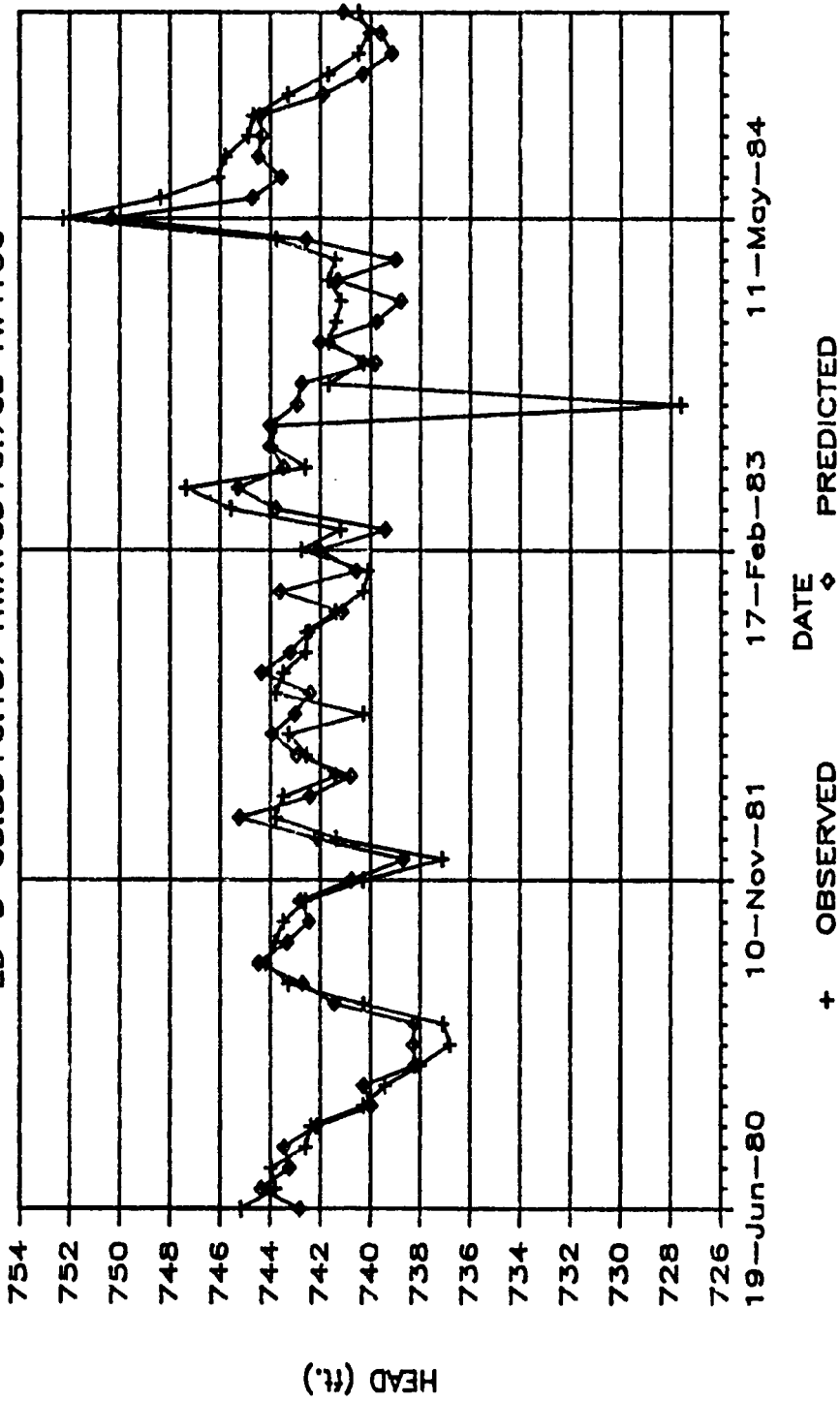


FIGURE A-47. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER ED-5

# REGRESSION MODEL : PIEZOMETER ED-6

$$ED-6=761.66+0.071*HW4TO6+0.016*TWAVG30$$

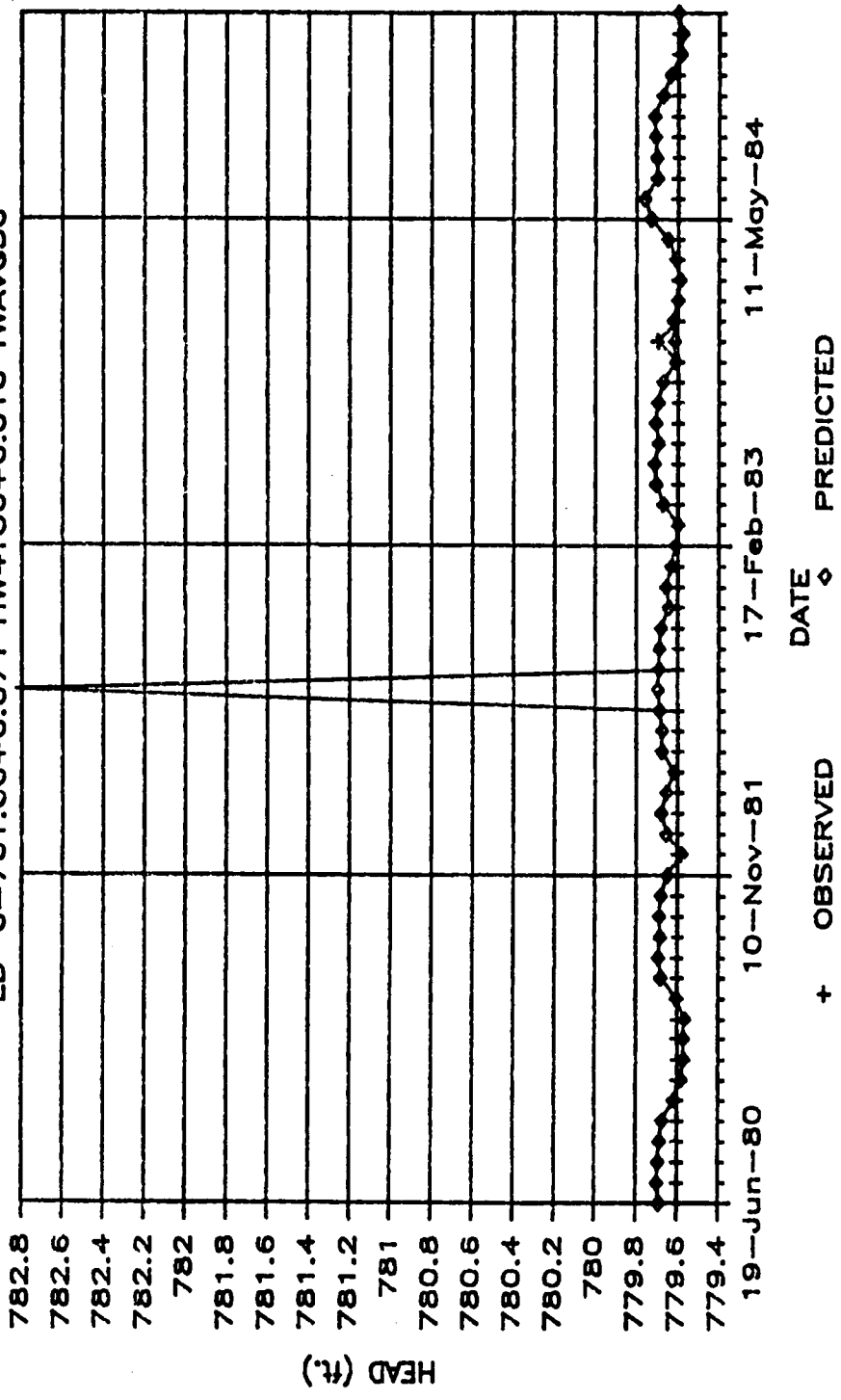


FIGURE A-48. PLOT OF OBSERVED VS PREDICTED HEAD FOR MULTIPLE REGRESSION ON PNEUMATIC PIEZOMETER ED-6

## VITA

James Howard French was born in Richmond, California, on June 5, 1955. He attended elementary schools in Alameda, California, and was graduated from Encinal High School in June 1972. He received a Bachelor of Arts degree in geology and geography from California State University, Chico, in May 1977. After graduating, he served as a research associate for 3 years with Union Carbide Corporation, Nuclear Division, in the field of uranium exploration. In 1981, he entered the University of Tennessee, Knoxville, as a full-time student, where he received a Bachelor of Science degree in Civil Engineering in June 1983.

After graduation from the University of Tennessee, he began service as a civil engineer with the Tennessee Valley Authority (TVA). He entered graduate school at the University of Tennessee in September 1983, and received a Master of Science degree in civil engineering in June 1986. At the time of graduation, the author was employed in TVA's Data Services Branch as a civil engineer.