3-1996

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Recommended Citation

Rowland, Jeffrey B., "A Response Surface Methodology Approach to Groundwater Model Calibration" (1996). *Theses and Dissertations*. 6231.
https://scholar.afit.edu/etd/6231

A RESPONSE SURFACE METHODOLOGY APPROACH TO GROUNDWATER MODEL CALIBRATION

THESIS

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THESIS

Presented to the Faculty of the Graduate School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Operations Research

Jeffrey B. Rowland, M.S.

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March 1996

THESIS APPROVAL

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THESIS TITLE: A Response Surface Methodology Approach to Groundwater Model Calibration

DEFENSE DATE: 05 March 1996

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Acknowledgments

My thanks go to my advisors, Lt. Col. Paul Auclair and Lt. Col. Dave Coulliette for their support of my research efforts. Without their help and advice, I would not have been able to complete my thesis. Without their guidance, I would have spent all my time chasing down useless side tracks instead of conducting meaningful research. My special thanks go to Lt. Col. Auclair for his patient and repeated explanations of statistical properties I had trouble understanding, and to Lt. Col. Coulliette for the time he spent helping me work the bugs out of the SUTRA command file that I put there. I would also like to thank Maj. Ed Heyse for his advice on appropriate bounds for the model input parameters. Finally, I would like to thank my fiancee Kelly Gillen for understanding my impatience and exhaustion, and for just being there.

Brett Rowland

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ABSTRACT

This thesis examined the effect of parameter bounding, a reduced data set, and data enrichment techniques on a response surface methodology (RSM) approach to groundwater model calibration. The four phases of the study included a calibration using a very dense data matrix, a calibration using a sparse calibration matrix, an evaluation of several data enrichment techniques, and a calibration using a data matrix enlarged with the use of the best enrichment technique. All calibrations were conducted using only a first order approximation to the response surface and with bounds placed on the input parameters. The first two calibrations using the dense and sparse data sets produced calibrated models which were very similar and very accurate. This led to the conclusion that reducing the size of the data set did not seriously degrade the calibration. The third calibration produced using the enriched data set produced results which were not as accurate as the first two calibrations and it required more calculations. Also, it was discovered that the use of a screening design would eliminate influential model parameters. All of the calibration methods provided accurate hydraulic head values, and final parameter values which were feasible.

A Response Surface Methodology Approach to Groundwater Model Calibration

I. Introduction

With the current concern for the state of our ecosystem, it should come as no surprise that hydrology--the study of the water we use to drink, bathe in, wash our cars, and water our lawns--is an important field. There are many sources of fresh water in the world. These include rivers, lakes, and ice. However, the majority of water used by the public comes from groundwater systems. These groundwater systems consist of networks of interconnected cracks, fissures, and openings in rocks, soils, and other porous media through which water can move (Cotman, 1995). Groundwater hydrologists study the properties, effects, and distribution of these groundwater systems. Often, the groundwater hydrologist uses numerical models to predict the flow of water through these systems (Anderson and Woessner, 1992: 1). These groundwater models are often implemented on computers and require certain parameters to be specified. Properly specifying these parameter values permits the model to accurately reflect the real world groundwater system; that is, the output of the groundwater model (usually hydraulic head values) conforms to that of the real world groundwater system (Anderson and Woessner, 1992: 223). The process of obtaining these correct parameter values is referred to as calibrating the model.

Cotman (1995) demonstrated that Response Surface Methodology could be used as an effective technique for calibrating groundwater models. However, he used a very dense target data set which, in real applications, would be costly and impractical to obtain. Also, some of Cotman's final calibrated parameter values were considered to be infeasible even though his predicted data set values conformed to the values in the calibration data set. Therefore, the purpose of this study was to determine the effects of a reduced data set and parameter bounds on the response surface calibration technique.

Determining the effects of the reduced data set and the parameter bounds was accomplished in four phases. First, bounds were placed on the parameter values and the model was calibrated using response surface methodology. Next, the data set was reduced and the model was calibrated once again using the reduced data set with the bounded parameters. Then several interpolating methods were compared to determine the effect of enriching the reduced data set. Finally, the best interpolating method was applied to the reduced data set and the model was calibrated a third time. After obtaining the three calibrations, the results were compared to each other and to the calibrations of Cotman (1995) and the original calibration obtained by Smith and Ritzi (1993).

II. Literature Review

Introduction

A well calibrated groundwater model produces hydraulic head values similar to those found in a calibration target data set. Calibration is accomplished by adjusting the input parameters until output values are within some error tolerance of the values in the target data set (Anderson and Woessner 1992: 223). Mathematically, calibrating a groundwater model is known as solving the inverse problem. The numerous mathematical methods available to solve the inverse problem and fall into two classes: "direct" and "indirect" methods (Neuman, 1973: 1006). "Direct" methods assume the model parameters are dependent variables of a flow equation. The parameters are found by solving a partial differential boundary problem (Carrera, 1988: 559). Some examples of the direct method of solving inverse problems include energy dissipation (Nelson, 1968), The Galerkin method (Frind and Prinder, 1973), and matrix inversion with kriging (Yeh and others, 1983). The "indirect" methods improve on the model output error by iteratively adjusting the input parameters until the model output falls within some error tolerance of the actual values. Examples of the indirect method include minimax and linear programming (Yeh and Becker, 1973), optimal control and gradient procedure (Vermuri and Karplus, 1969), and maximum likelihood estimation and kriging (Kitanidis and Vomvoris, 1983). Response surface methodology falls under the category of an "indirect" method. For a more extensive list of the "direct" and "indirect" methods used to solve the inverse problem, refer to Cotman (1995).

The purpose of this study was to determine the effect of parameter bounding and data reduction on a groundwater model calibration using response surface methodology. This chapter reviews response surface methodology and data enrichment techniques which can be used to increase the size of a data set.

Overview of Response Surface Methodology

"Response surface methodology comprises a group of statistical techniques for empirical model building and model exploitation. By careful design and analysis of experiments, it seeks to relate a *response*, or *output* variable to the levels of a number of *predictors*, or *input* variables, that affect it" (Box and Draper, 1987: 1). In the case of groundwater model calibration, the predictor variables are the input hydrogeological parameters of the model and the response is a measure used to determine how well the model's predicted values match a calibration target data set. In conducting a response surface methodology calibration, an iterative four step process of conjecture—design—experiment—analysis is used (Box and Draper, 1987: 7).

> Most response surface investigations are sequential in nature. At first an idea or conjecture is formed concerning which factors are important in terms of influencing some particular response of interest. This leads to planning or designing an experiment that can conceivably perform a dual role; to verify that the factors thought to be important are indeed influential, and to eliminate (weed out) factors that are unimportant. The experiment is then performed and the data are collected. The data are analyzed and the results lead to new ideas or conjectures (Khuri and Cornell, 1987: 15).

These four steps are normally completed throughout three distinct phases in a typical RSM study. The first step is a screening phase, which is used to investigate the input parameters and to eliminate those which do not significantly affect the output, or response. The second phase of the study is used to determine if the current settings of the input parameters result in a response that is near optimum or if the parameters need to be adjusted to improve the response. This phase approximates the response surface with a first order model and seeks to improve the response obtained through the use of designed experiments and the method of steepest ascent (or descent). The third phase begins when the first-order design phase no longer improves the response. This phenomenon usually occurs when the process is near the optimum because the true response surface usually exhibits curvature in this region. During this phase, a second-order model is fit to areas of the response surface in order to determine the optimum parameter settings for the process (Myers and Montgomery 1995: 10-11). However, these three steps are only the tools of RSM; how they are utilized is up to the experimenter.

One advantage of response surface methodology is that it never seeks to approximate the entire response surface. Several methods have been examined which use the error statistics and gradient search methods used by response surface methodology (Dettinger and Wilson, 1981, Sun and Yeh, 1985, Sykes, Wilson, and Andrews, 1985, Townley and Wilson, 1985, Wilson and Metcalfe, 1985). However, these methods all attempt to approximate the entire response surface, whereas response surface methods estimate the response surface at each step in the study only in the region defined by an experimental design.

Design of Experiments

A fundamental part of any response surface study is the design used. A design is a collection of experiments used to determine the effects of the input parameters on the response. A properly designed experiment prescribes the data to be collected and analyzed, and provides a basis for valid and objective conclusions (Montgomery, 1976: 2).

Response surface methodology experiments frequently employ two-level designs, in which each parameter is tested at a high and a low level. Typically the parameters are coded as

$$x_k = \frac{\xi_k - \xi_{k0}}{S_k} \qquad \text{(2-1)}$$

where ξ_κ is the parameter, $\xi_{\kappa 0}$ is the center of the range of the parameter ξ_κ, and S_k is the half width of the range. This formula transforms each parameter to a value of 1 at the high level and -1 at the low level. Using coded parameters simplifies the numerical calculations used in the response surface study (Khuri and Cornell, 1987: 10).

The two-level design used to estimate the effects of k design parameters is called a 2^k factorial design because the design has exactly 2^k experimental trials (Myers and Montgomery, 1995: 79). The class of 2^k factorial designs are very important in response surface studies because:

1. A 2^k design is useful at the start of a response surface study where screening experiments should be performed to identify the important process or system variables in phase 1 of the response surface study.
2. A 2^k design is often used to fit a first-order response surface model and to generate the factor effect estimates required to perform the method of steepest ascent (or descent) in phase 2 of the study
3. The 2^k design is a basic building block used to create other response surface designs such as central composite designs. A central composite design is one the most important designs for fitting second-order response models which are used in phase three of the response surface study. (Myers and Montgomery, 1995: 79)

Sometimes the size of the resulting design precludes using a full 2^k design. For example, the calibration in this study includes 11 parameters, and a full 2^{11} design would include 2048 experiments. Fortunately, it is possible to use a fraction of the full design if interactions between the main effects are ignored. For this study, it was assumed that only the effects of the parameters were important and interactions between parameters could be disregarded. This simplifying assumption allowed the use of a special type of design called a Plackett-Burman design. Plackett-Burman designs are fractions of full 2^k designs, and they are used for studying $k = N-1$ variables in N runs, where N is a multiple of 4 (Box and Draper, 1987: 162). In this study, 11 parameters were studied, and the use of a Plackett-Burman design allowed the estimation of the effects of these parameters using only 12 experimental runs.

The concept of experimental design is fundamental to any response surface study since some type of design is used in every phase of the study. The type of design utilized is determined by the experimenter, but any design used should allow all relevant effects to be estimated. Limiting the size of the design allows the process under investigation to be optimized as efficiently as possible

Parameter Screening

An important step in response surface methodology is to reduce the number of experiments because typically each experiment has a certain cost associated with it. The parameter screening phase determines which input parameters significantly affect the response, and the size of the designs used in subsequent stages of the response surface process is reduced by adjusting only these parameters.

The parameter screening phase relies on a two-level experimental design. Once the specific design is determined and the experiments are run, the responses, Y_u, are fit to a first-degree polynomial model in k coded variables, x_{ui} ($i = 1 \ldots k$), with the general form (Cornell, 1990: 13)

$$Y_u = \beta_0 + \beta_1 x_{u1} + \beta_2 x_{u2} + \ldots + \beta_k x_{uk} + \varepsilon_u \tag{2-2}$$

The β_k coefficients are proportional to the effect the kth coefficient has on the response ($\text{Effect}_k = 2\beta_k$). One method for determining which effects are significant is through the use of a normal probability plot. In a properly fit first-order linear model, the residuals are approximately normally distributed with equal variance. If none of the effects are significant, then the residuals should appear to be normally distributed. The cumulative distribution of the normally distributed residuals, when plotted on normal probability paper, should appear as a straight line. Any points which fall considerably off this straight line could be assumed to have a significant effect on the response. The probability plot can also be accomplished on normal graph paper by ordering the effects and plotting them against the quantity $\phi^{-1}[(i - 0.5)/k$, where $\phi^{-1}(p)$ is the inverse cumulative distribution function of the standard normal distribution and i is the rank of the effect. By examining this graph, the experimenter can determine which effects appear to significantly affect the response.

First Order Design Phase

The first order design phase is a sequential process which seeks to improve the response through the use of a two-level design, a first order model, and a gradient search technique known as the method of steepest ascent (Myers and Montgomery, 1995: 11).

First, the experiments defined by the design are conducted and the responses are obtained. The response surface is then approximated using a first-order model (equation 2-2), and the gradient of the estimated response surface with respect to the design parameters is computed. Since the estimated function is linear, the gradient is defined by the estimated coefficients (β_i's). Experiments are conducted along the path of the gradient away from the center of the design region until the response value obtained from the experiment no longer improves. If a larger response is sought, experiments are conducted in the positive gradient direction. In seeking a smaller response the experiments are conducted in the negative gradient direction. Once the experiments stop producing improvements in the response value, a new design is established in the region of the experiment which gives the best response. At this point the process is started once again, by computing the new estimated model gradient and repeating the iterative process of improving the response.

This process continues until the first order model no longer provides an adequate approximation to the response surface, and there are several methods of determining when this point has been reached. One of these methods is the single degree of freedom test for curvature as discussed by Myers and Montgomery (1995: 112-113). The lack of fit test provides statistical evidence that a first order model is no longer adequate. Also, if experiments conducted along the gradient path fail to produce improvement or produce insignificant improvement, then a first order model is no longer sufficient. At the point where the first order design phase is halted, the experimenter must determine whether the best response obtained is "good enough," or if a higher order approximation to the response surface is required.

Second Order Design Phase

A second order design phase is conducted in a response surface study when the first order model no longer sufficiently approximates the response surface but the response values obtained are not yet within a tolerance of an optimal value. The results obtained by Cotman showed that a second order model offered minimal improvements over the results obtained from the first order design phase in calibrating the groundwater model used in this study. Also, the choice of a response which exhibited less curvature than the one used by Cotman eliminated the need for a second order design phase. Therefore, this study used only the first order design phase in an effort to calibrate the groundwater model.

Data Enrichment Techniques

In the course of any statistical study, it may become apparent that the amount of data available is insufficient to complete the study. Data enrichment techniques expand upon a given data set by estimating values at points where data was not actually observed or collected. The methods examined in this study all involve weighted linear combinations of the form

$$\text{estimate} = \hat{v} = \sum_{i=1}^{n} w_i v_i \qquad (2\text{-}3)$$

where $v_1,\ldots,v_n$ are the n available data values and w_i is a weight assigned to the value v_i. The differences in the methods arise from how the weights, w_i, are assigned to the known data values. Weighting can be accomplished through common sense notions about which data values are more important or it can be based on statistical theory (Isaaks and Srivastava, 1989: 185). The methods of data enrichment evaluated in this study were inverse distance methods and kriging.

The simplest data enrichment technique weights each value equally. However, the data values closest to the point where an estimate is made will normally be more indicative of the true data value than those that are farther away. Therefore, weights could be assigned by making them inversely proportional to their distance from the estimate. This criterion is the basis for the inverse distance methods of point estimation. The estimated point is given by

$$\hat{v}_i = \frac{\sum_{i=1}^{n} \frac{1}{d_i^{\,p}} v_i}{\sum_{i=1}^{n} \frac{1}{d_i^{\,p}}} \qquad (2\text{-}4)$$

where d_i represents the distance from the point v_i to the point being estimated, and p is an exponent that allows the weights to be inversely proportional to any power of the distance. The inverse distance formula given above offers considerable flexibility. As p approaches 0, the weights become more similar, and as p becomes larger, the nearest points receive more weight (Isaaks and Srivatava, 1989: 258-259).

Kriging is another estimation method which uses a weighted linear combination (equation 2-3) of the available values to produce new sample values. The method of kriging uses best linear unbiased estimators in order to produce point estimates. The point estimates in kriging are developed by ensuring that the expected error of any point estimate is equal to zero and that the error variance is minimized by first assuming n + 1 random variables, n of which model the behavior of the phenomenon at the known sample values and one of which models its behavior at the location being estimated. The weights for the formula are then obtained by solving the following n + 1 equations

$$\begin{aligned} &\sum_{j=1}^{n} w_j \tilde{C}_{ij} + \mu = \tilde{C}_{i0} \quad \forall i = 1,\ldots,n \\ &\sum_{i=1}^{n} w_i = 1 \end{aligned} \tag{2-5}$$

where $\tilde{C}_{ij}$ is the estimated covariance between the sample values v_i and v_j, $\tilde{C}_{io}$ is the estimated covariance between the sample value v_i and the point being estimated, and μ is a Lagrange parameter. This system of equations can be written in matrix notation as

$$\begin{array}{ccccc} \mathbf{C} & \cdot & \mathbf{w} & = & \mathbf{D} \\ \begin{bmatrix} \tilde{C}_{11} & \cdots & \tilde{C}_{1n} & 1 \\ \vdots & \ddots & \vdots & \vdots \\ \tilde{C}_{n1} & \cdots & \tilde{C}_{nn} & 1 \\ 1 & \cdots & 1 & 0 \end{bmatrix} & \cdot & \begin{bmatrix} w_1 \\ \vdots \\ w_n \\ \mu \end{bmatrix} & = & \begin{bmatrix} \tilde{C}_{10} \\ \vdots \\ \tilde{C}_{n0} \\ 1 \end{bmatrix} \end{array} \tag{2-6}$$

multiplying both sides of equation (2-6) by $\mathbf{C}^{-1}$, the inverse of the covariance matrix, yields the solution $\mathbf{w} = \mathbf{C}^{-1} \cdot \mathbf{D}$. Therefore, in order to obtain the weights which produce the best linear unbiased estimates it is necessary to choose $(n + 1)^2$ covariances which describe the spatial continuity of the data. In practice this is typically done by choosing a function $\tilde{C}(\mathbf{h})$, and calculating all of the required covariances from this function (Isaaks and Srivastava, 1989: 287-288). After the covariances have been estimated the **C** and **D** matrices can be determined and the weights can be computed. The method of kriging is a useful tool in data estimation because it attempts to take the spatial continuity of the data into account when producing estimates.

III. Methodology and Results

Background

The purpose of this study was to develop, or calibrate, a groundwater model using response surface methodology. The groundwater modeling program used in this study, SUTRA (Saturated-Unsaturated TRAnsport), was developed by the United States Geological Survey (Voss, 1984:3). SUTRA divides the cross-section of the groundwater system into contiguous blocks, called elements as depicted in Figure 3.1. The corners of the elements are called nodes and regions centered at the nodes are termed cells.

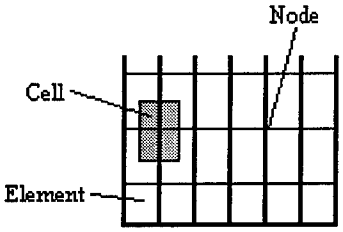

Figure 3.1 Graphical Representation of Elements, Nodes, and Cells

A grid of these interconnected nodes is constructed on a cross section of the groundwater system. The spacing and frequency of the nodes are set to accurately reflect the hydrogeological nature of the groundwater system (Cotman, 1995: 3-8).

Each execution of SUTRA requires a value for hydraulic conductivity and porosity for each element in the grid. SUTRA uses this input to calculate steady-state fluid pressures at every node in the grid. These pressures are then converted to hydraulic head values using the equation

$$h = z + \frac{p}{\rho g} \tag{3-1}$$

where z (m) is the elevation of the measured point above a level reference height, p (g kg/m^2) is the fluid pressure, ρ (kg/m^3) is the density of the fluid, and g (m/min^2) is the acceleration due to gravity. These hydraulic head values can then be compared to the calibration target data set in order to assess the model's accuracy. In order to simplify the execution of SUTRA and the reporting of its results, the VMS command file and post processor file created by Cotman (1995: Appendix B and C) were used.

Calibration

The process of iteratively adjusting the model input parameters until the estimated hydraulic head values are within some error tolerance of the target data set is termed calibration. As stated above, each execution of SUTRA produced a set of hydraulic head values which are then compared to the calibration target data set in order to determine their accuracy. Each hydraulic head value produced by SUTRA (h_s) was compared to the corresponding hydraulic head value in the calibration target data set (h_m) in order to compute residual statistics. For this study, four residual statistics were computed after every execution of SUTRA; they were the Sum of Squared Error (SSE), the Root Mean Squared Error (RMS), The Mean Absolute Error (MAE), and the Mean Error (ME)

$$SSE = \sum_{i=1}^{n} (h_m - h_s)_i^2 \qquad (3\text{-}2)$$

$$RMS = \sqrt{\left(\frac{1}{n}\sum_{i=1}^{n} (h_m - h_s)_i^2\right)} \qquad (3\text{-}3)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n} \left|(h_m - h_s)_i\right| \qquad (3\text{-}4)$$

$$ME = \frac{1}{n}\sum_{i=1}^{n} (h_m - h_s)_i \qquad (3\text{-}5)$$

where n is the number of nodes in the grid (Anderson and Woessner, 1992: 238-241). During the calibrations using response surface methodology, input parameters were simultaneously adjusted using RSM techniques until a suitably small residual statistic was computed using one of the above formulas applied to the SUTRA output.

The Study

This study included four distinct phases. The first involved calibrating the groundwater model using the full calibration target data set of 524 nodes used by Cotman (1995) with bounds placed on the values of each input parameter in order to create a "feasible region". The second phase calibrated the model using a target data set with a reduced number of nodes (24), representing a more realistic target data set. The third phase evaluated several data enrichment techniques used to increase the size of the reduced data set back to 524 nodes. These enriched data sets were compared to the original calibration target data set to determine which data enrichment technique provided the best estimates of hydraulic head values throughout the groundwater system. The final phase calibrated the groundwater model using the target data set created from the best data enrichment technique.

Calibration Target Data Set Preparation

The target data set used in the calibration process was generated from a model calibrated by Smith and Ritzi (1993). This model was used to simulate groundwater flow and nitrate transport on the Sycamore Farm research facility of Wright State University, Ohio. A complete hydrogeologic description of the Sycamore Farm area is provided in Smith (1991: 55-56). Using a previously calibrated model to create a target data set had the advantages of eliminating uncertainties due to field measurement errors and providing hydraulic head values at each computational node in the groundwater system. Although such resolution is unrealistic for field application, it is often used as a validation technique (Xiang and others, 1993; Carrera and Neuman, 1986).

The Groundwater System

The groundwater system used in this study consisted of ten hydraulic conductivity zones as shown in Figure 3.2.

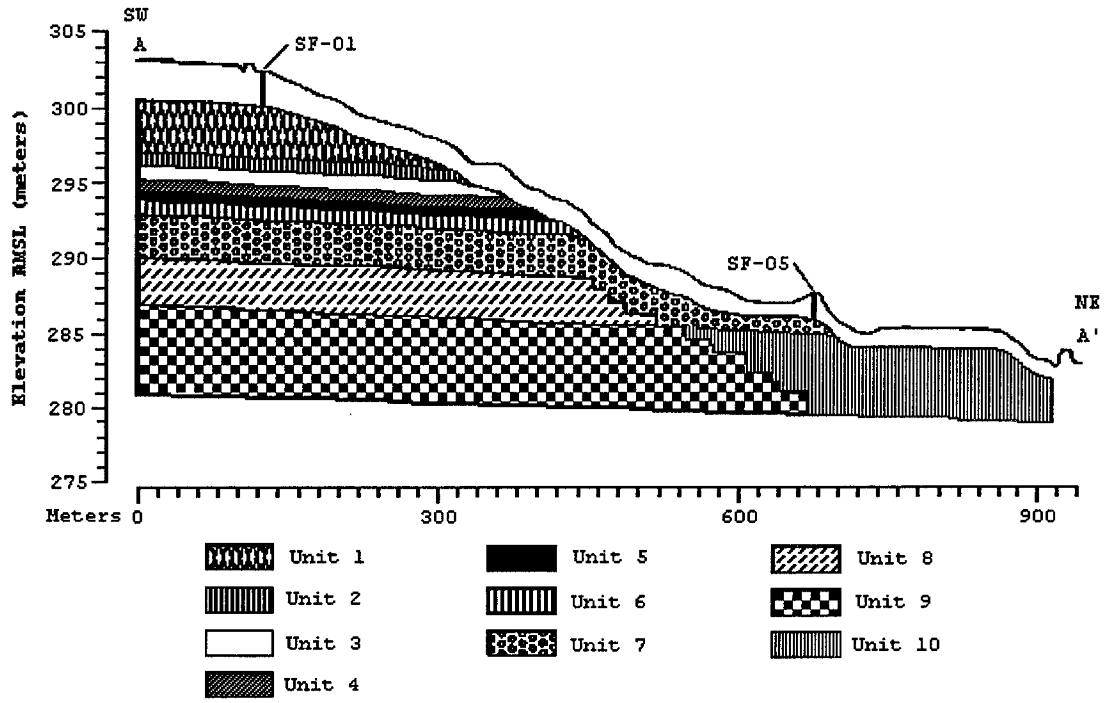

Figure 3.2 Hydraulic Conductivity Zones

The input parameter set used during the calibration process consisted of a hydraulic conductivity value for each zone and an overall porosity value for the entire groundwater system. At the beginning of the study, bounds were placed on the hydraulic conductivities and the porosity to create a "region of feasibility" for the input parameters. During the calibration process, the values for the input parameters were not allowed to vary outside these ranges (Table 3.1).

Table 3.1 Parameter Bounds

Parameter	Lower Bound	Upper Bound
Porosity	.06	.16
Unit 1	1.0×10^{-5}	1.0×10^{-1}
Unit 2	1.0×10^{-6}	1.0×10^{-2}
Unit 3	1.0×10^{-6}	1.0×10^{-2}
Unit 4	1.0×10^{-6}	1.0×10^{-2}
Unit 5	1.0×10^{-6}	1.0×10^{-2}
Unit 6	1.0×10^{-6}	1.0×10^{-2}
Unit 7	1.0×10^{-7}	1.0×10^{-3}
Unit 8	1.0×10^{-7}	1.0×10^{-3}
Unit 9	1.0×10^{-7}	1.0×10^{-4}
Unit 10	1.0×10^{-7}	1.0×10^{-4}

Each execution of SUTRA produced a data set containing the horizontal (X) and vertical (Y) coordinates as well as the hydraulic pressure for each of the 524 nodes in the finite element grid shown in Figure 3.3.

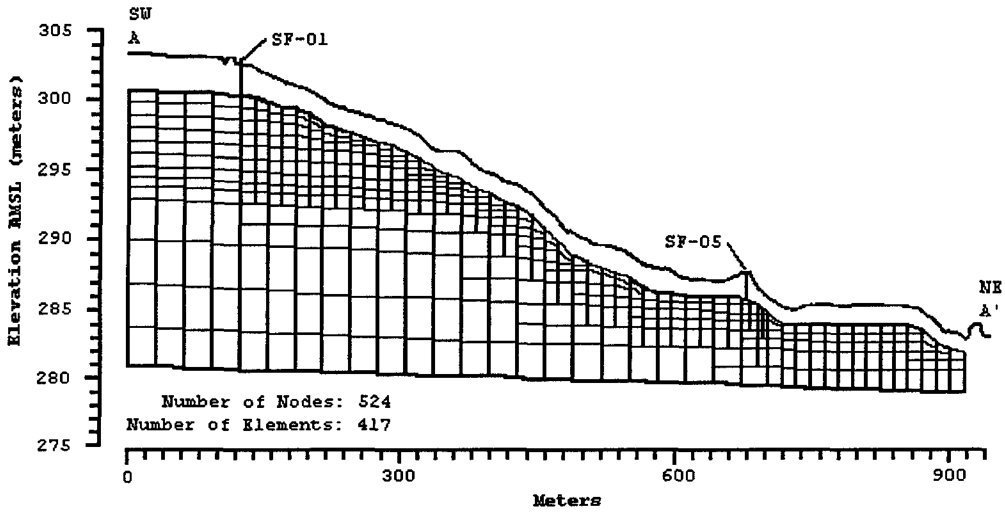

Figure 3.3 Cross-Sectional Grid

The values of hydraulic pressure which were output from SUTRA were then transformed into hydraulic head values using Equation 3-1, and compared to the calibration target data set by computing the statistics described in Equations 3-2 to 3-5.

Full Target Data Set Calibration

The first phase of the study involved calibrating the model using the full calibration target data set of 524 nodes and the bounds on the parameters as described in Table 3.1. This calibration was used as a comparison to the calibration accomplished by Cotman (1995) and to the subsequent two calibrations accomplished during this study. The first step in the calibration was to conduct a screening experiment over the entire bounded parameter space to determine which parameters influenced the response and to determine a good starting point for the first order phase. This step was accomplished using a two-level Plackett-Burman design with 12 runs. Table 3.2 shows the design; a value of +1 indicates that the parameter was set at its high level, and a value of -1 indicates the low level.

Table 3.2 Plackett-Burman Design

Run	Porosity	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	+1	-1	+1	-1	-1	-1	+1	+1	+1	-1	+1
2	+1	+1	-1	+1	-1	-1	-1	+1	+1	+1	-1
3	-1	+1	+1	-1	+1	-1	-1	-1	+1	+1	+1
4	+1	-1	+1	+1	-1	+1	-1	-1	-1	+1	+1
5	+1	+1	-1	+1	+1	-1	+1	-1	-1	-1	+1
6	+1	+1	+1	-1	+1	+1	-1	+1	-1	-1	-1
7	-1	+1	+1	+1	-1	+1	+1	-1	+1	-1	-1
8	-1	-1	+1	+1	+1	-1	+1	+1	-1	+1	-1
9	-1	-1	-1	+1	+1	+1	-1	+1	+1	-1	+1
10	+1	-1	-1	-1	+1	+1	+1	-1	+1	+1	-1
11	-1	+1	-1	-1	-1	+1	+1	+1	-1	+1	+1
12	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1	-1

The high and low value for each of the input parameters represented their upper and lower bounds as presented in Table 3.1. The complete results of each experiment are listed in Appendix A. Each of these 12 experiments was run through SUTRA, and the error statistics were computed. The RMS statistic was utilized throughout this study to determine the accuracy of the model output because it provided a flatter response surface than the SSE statistic used by Cotman (1995). To determine which parameters influenced the response, a normal probability plot was produced (Figure 3.4). The effects of units 5, 6, 8, and 9 appear to fall off the line through the other effects, indicating that only those input parameters influence the response. The fact that only four parameters fall off the line implies that a 2^4 full factorial design with 16 experimental runs could be used in the first order design phase with units 5, 6, 8 and 9 being allowed to vary and all other input parameters fixed. However, using a Plackett-Burman design allowed the effects of all 11 parameters to be estimated in only 12 runs, and it allowed all of the input parameters to be adjusted as improvements in response were sought. Allowing all of the

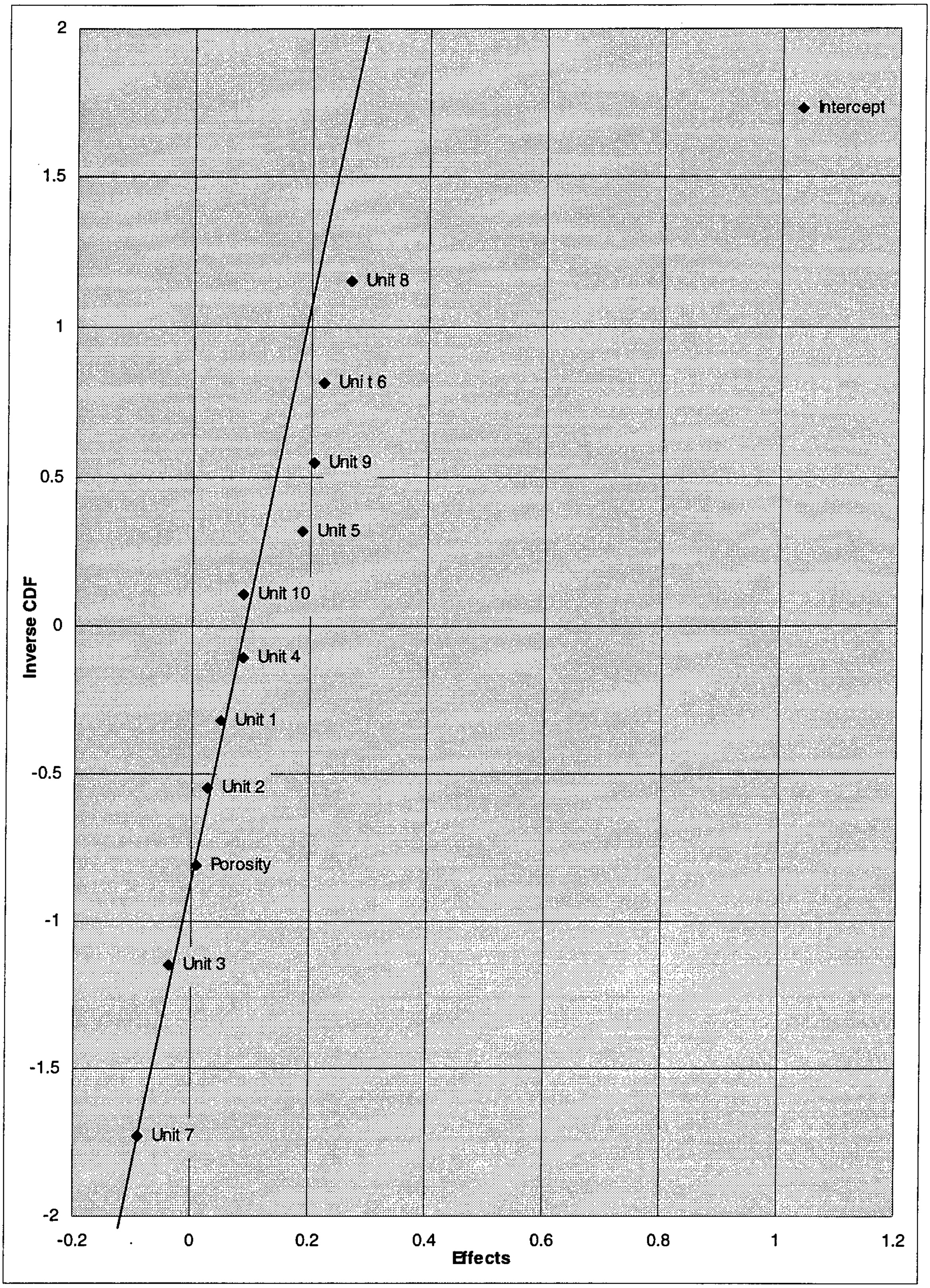

Figure 3.4 Normal Probability Plot
Full Target Data Set

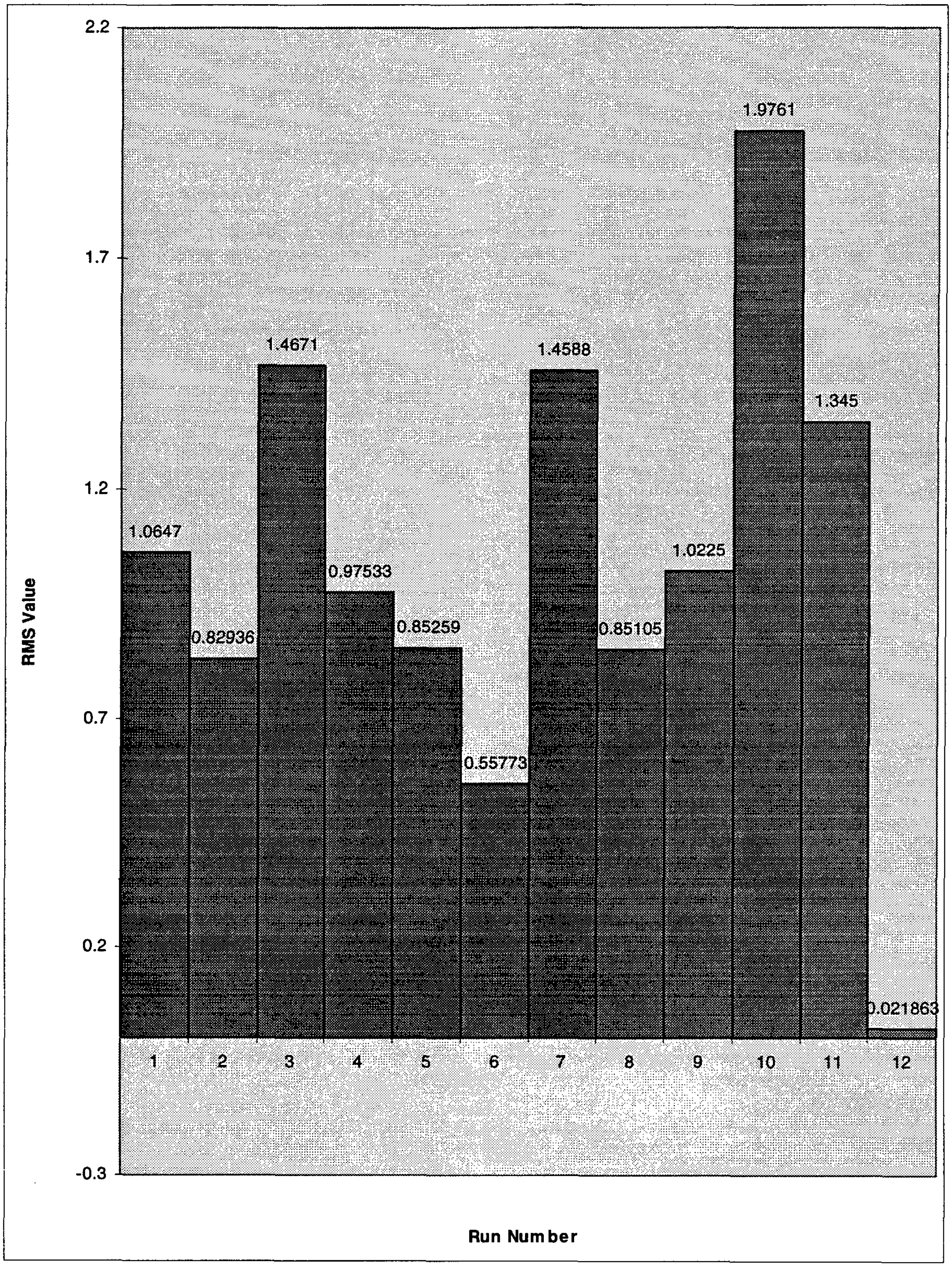

Figure 3.5 Screening Design RMS Values
Full Target Data Set

parameters to vary was beneficial because the results obtained during the course of the calibration showed that parameters which influenced the response would have been screened out of subsequent experiments had the results from the normal probability plot been used.

Figure 3.5 compares the RMS results obtained from each experiment of the screening design. Any run which exhibited a low value of RMS was a good candidate for a starting point for the first-order design phase. Examining Figure 3.5 showed that run 12 had an RMS value that was noticeably lower than the values for the other experimental runs. Therefore, the starting point for the first-order design phase was based on the settings used for experiment 12 in the screening design.

Design A

The settings used in design A were based on the Plackett-Burman design with 12 runs (Table 3.2). The low levels of each design point were determined from the screening design experiment with the lowest RMS value (run 12). The range of each hydraulic conductivity was designed to cover one order of magnitude. The high and low settings for each parameter are shown in Table 3.3. The responses obtained from each experiment are shown in Table 3.4.

Table 3.3 Design A Parameter Settings Full Target Data Set

Parameter	High Setting	Low Setting
Porosity	.16	.06
Unit 1	9.0×10^{-5}	1.0×10^{-5}
Unit 2	9.0×10^{-6}	1.0×10^{-6}
Unit 3	9.0×10^{-6}	1.0×10^{-6}
Unit 4	9.0×10^{-6}	1.0×10^{-6}
Unit 5	9.0×10^{-6}	1.0×10^{-6}
Unit 6	9.0×10^{-6}	1.0×10^{-6}
Unit 7	9.0×10^{-7}	1.0×10^{-7}
Unit 8	9.0×10^{-7}	1.0×10^{-7}
Unit 9	9.0×10^{-7}	1.0×10^{-7}
Unit 10	9.0×10^{-7}	1.0×10^{-7}

Table 3.4 Design A Summary Statistics Full Target Data Set

Run	SSE	RMS	MAE	ME
1	0.1348	0.0160	0.0091	-0.0005
2	0.1971	0.0194	0.0102	-0.0025
3	0.9330	0.0422	0.0215	0.0010
4	0.8870	0.0411	0.0212	0.0023
5	0.5179	0.0314	0.0157	0.0015
6	0.1734	0.0182	0.0091	-0.0018
7	0.3251	0.0249	0.0123	-0.0030
8	0.2435	0.0216	0.0110	-0.0014
9	0.2465	0.0217	0.0115	-0.0008
10	0.6597	0.0355	0.0184	-0.0012
11	0.1756	0.0183	0.0097	0.0012
12	0.2505	0.0219	0.0122	-0.0020

A first order model was fit to the RMS responses using the Regression Analysis Tool from *Microsoft Excel*. The results obtained are summarized in Table 3.5.

Table 3.5 Design A Steepest Descent Vector
Full Target Data Set

	Regression Coefficients	Direction of Steepest Descent	Steepest Descent Unit Vector
Porosity	0.0009	-0.0009	-0.1057
Unit1	-0.0003	0.0003	0.0316
Unit2	0.0013	-0.0013	-0.1501
Unit 3	0.0007	-0.0007	-0.0761
Unit 4	0.0024	-0.0024	-0.2734
Unit 5	0.0006	-0.0006	-0.0684
Unit 6	-0.0014	0.0014	0.1584
Unit 7	-0.0068	0.0068	0.7745
Unit 8	0.0006	-0.0006	-0.0683
Unit 9	0.0037	-0.0037	-0.4158
Unit 10	0.0025	-0.0025	-0.2784

The first column provides the coefficients from the first order equation. The numbers in the second column are the negatives of the regression coefficients since the additive inverse of the regression coefficients defines the path of steepest descent. The third column is the normalized steepest descent vector, and was used to determine the parameter values used in conducting experiments along the steepest descent path. Notice that the values for units 4 and 10 indicate that these two units exert a considerable influence the response. However, the effects of these two units would have been screened from the calibration had the results of the normal probability plot been used.

Experiments were conducted along the path of steepest descent until the RMS response failed to decrease. Figure 3.6 illustrates the behavior of the RMS response along the steepest descent gradient. The lowest RMS value occurred 18 unit vector lengths from the center of design region A. The RMS response value decreased from the lowest value of design A (0.0160) to a value of 0.0087.

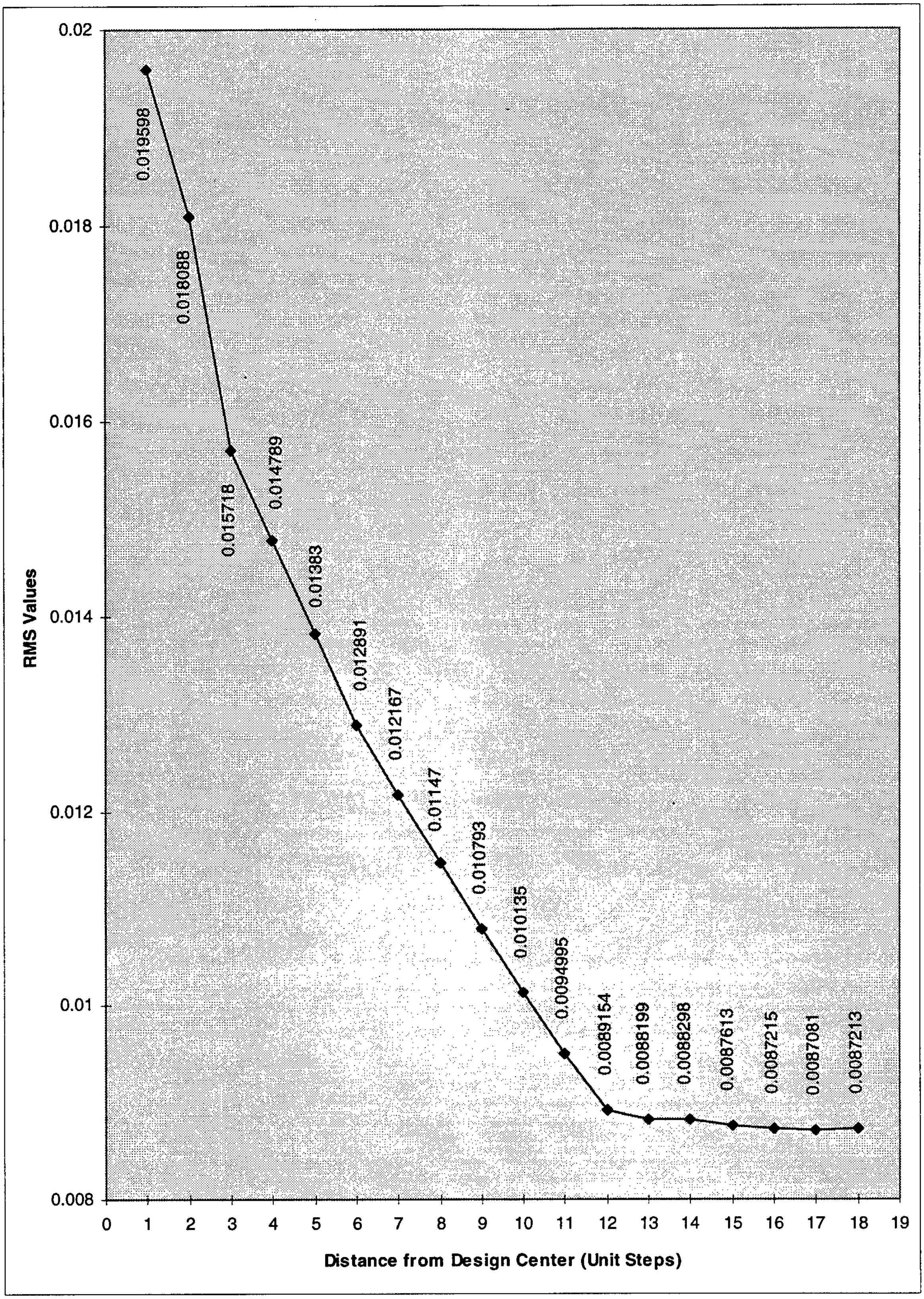

Figure 3.6 Design A Steepest Descent
Full Target Data Set

Design B

Design B was constructed using the design point with the minimum RMS value from the gradient search emanating away from design A. The high and low settings for the parameters are shown in Table 3.6, and the summary statistics are given in Table 3.7.

Table 3.6 Design B Parameter settings
Full Target Data Set

Parameter	Lower Bound	Upper Bound
Porosity	.06	.08
Unit 1	3.2761×10^{-5}	1.1276×10^{-4}
Unit 2	1.0000×10^{-6}	1.0000×10^{-6}
Unit 3	1.0000×10^{-6}	1.0000×10^{-6}
Unit 4	1.0000×10^{-6}	1.0000×10^{-6}
Unit 5	1.0000×10^{-6}	1.0000×10^{-6}
Unit 6	1.2408×10^{-5}	2.0408×10^{-5}
Unit 7	2.0766×10^{-6}	1.0077×10^{-5}
Unit 8	1.0000×10^{-7}	1.0000×10^{-7}
Unit 9	1.0000×10^{-7}	1.0000×10^{-7}
Unit 10	1.0000×10^{-7}	1.0000×10^{-7}

Table 3.7 Design B Summary Statistics
Full Target Data Set

Run	SSE	RMS	MAE	ME
1	0.0470	0.0095	0.0033	0.0011
2	0.0675	0.0114	0.0048	0.0004
3	0.0930	0.0133	0.0073	-0.0016
4	0.1010	0.0139	0.0069	-0.0011
5	0.0990	0.0137	0.0070	-0.0007
6	0.0588	0.0106	0.0052	-0.0002
7	0.0935	0.0134	0.0072	-0.0022
8	0.0916	0.0132	0.0060	-0.0002
9	0.0986	0.0137	0.0068	0.0003
10	0.1076	0.0143	0.0073	-0.0006
11	0.0516	0.0099	0.0049	0.0026
12	0.0573	0.0105	0.0057	-0.0005

A first order model was fit to the RMS responses and experiments were conducted along the path of steepest descent (Table 3.8).

Table 3.8 Design B Steepest Descent Vector Full Target Data Set

	Direction of Steepest Ascent	Direction of Steepest Descent	Steepest Descent Unit Vector
Porosity	-0.0004	0.0004	0.1009
Unit1	0.0010	-0.0010	-0.2285
Unit2	0.0005	-0.0005	-0.1158
Unit 3	0.0008	-0.0008	-0.1869
Unit 4	0.0008	-0.0008	-0.1806
Unit 5	-0.0003	0.0003	0.0774
Unit 6	-0.0003	0.0003	0.0714
Unit 7	-0.0028	0.0028	0.6407
Unit 8	-0.0026	0.0026	0.5944
Unit 9	0.0008	-0.0008	-0.1906
Unit 10	0.0009	-0.0009	-0.2132

The behavior of the RMS response along the steepest descent gradient is summarized in Figure 3.7. After 2 steps along the steepest descent gradient, the RMS value stopped decreasing. The minimum RMS value (0.0068) represented only a marginal decrease over the best value observed during the design A gradient search (0.0087). Therefore, the response surface process was halted and the parameter values for step 2 of the design B gradient search were used as the calibrated parameters. The values are presented in Table 3.9.

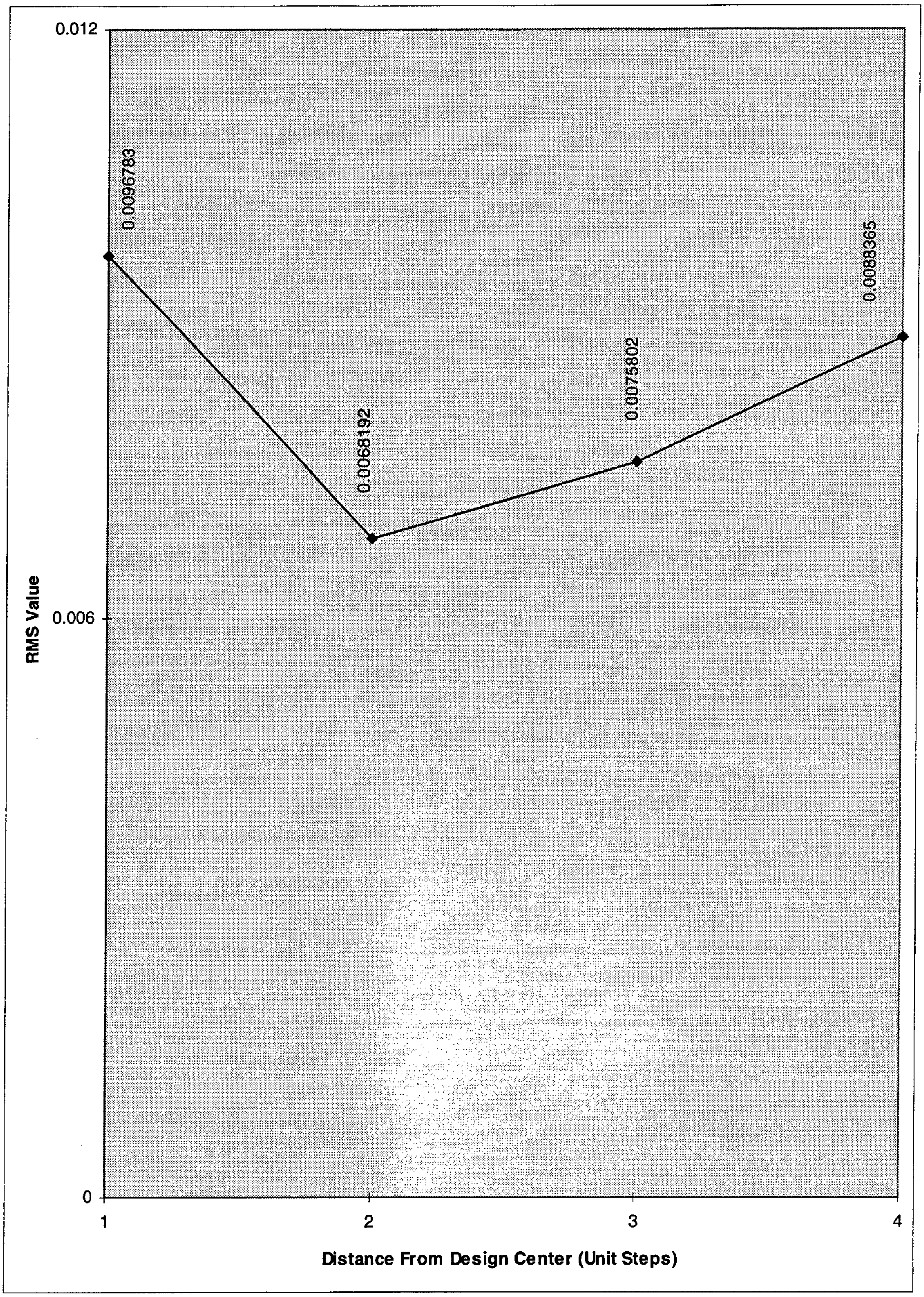

Figure 3.7 Design B Steepest Descent
Full Target Data Set

Table 3.9 Calibrated Parameter Values
Full Target Data Set

Parameter	Calibrated Value
Porosity	.07
Unit 1	8.3731 x 10^{-5}
Unit 2	2.9358 x 10^{-6}
Unit 3	1.0000 x 10^{-6}
Unit 4	1.0000 x 10^{-6}
Unit 5	2.1704 x 10^{-6}
Unit 6	1.6759 x 10^{-5}
Unit 7	1.0635 x 10^{-5}
Unit 8	2.2655 x 10^{-7}
Unit 9	2.0786 x 10^{-7}
Unit 10	2.8542 x 10^{-7}

Reduced Target Data Set Calibration

For the second calibration, the target data set was reduced to the 24 nodes under the two wells in the groundwater system (Figure 3.8), in order to more accurately reflect data which would be available from actual field measurements.

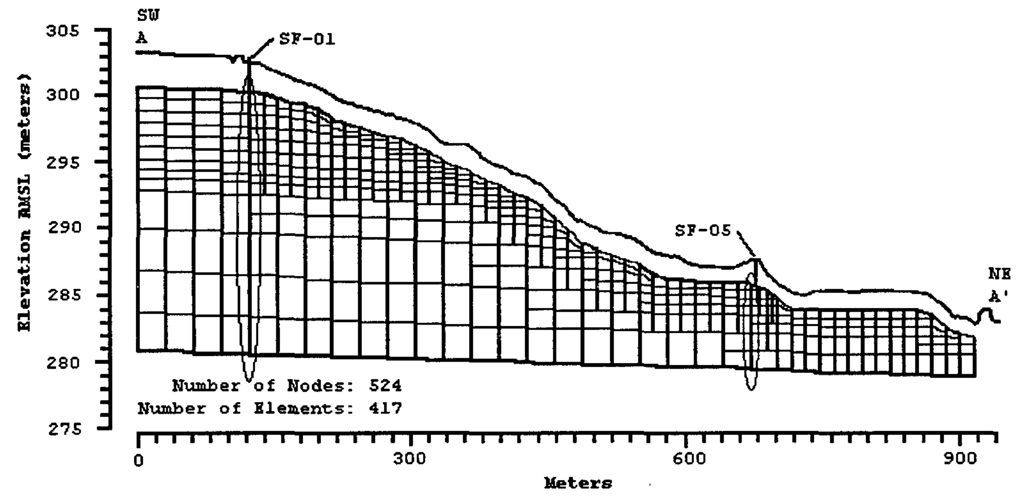

Figure 3.8 Placement of Nodes used in the Reduced Target Data Set Calibration

A screening experiment was conducted with the same design (Table 3.2) and parameter levels (Table 3.3) used for the full target data set calibration. The normal probability plot (Figure 3.9) of the input parameters showed that units 4, 5, 6, 8, 9, and 10 might differ significantly from the straight line through the other effects. Once again, however, a Plackett-Burman design allowed the response surface procedure to estimate all 11 parameters with only 12 experimental runs. Also, the use of the Plackett-Burman design prevented the inadvertent screening of influential effects. Therefore, the Plackett-Burman design was once again used during the calibration process.

The comparison of the experimental runs from the screening design (Figure 3.10) showed experimental run 12 offered the lowest RMS value and was therefore used to create design A.

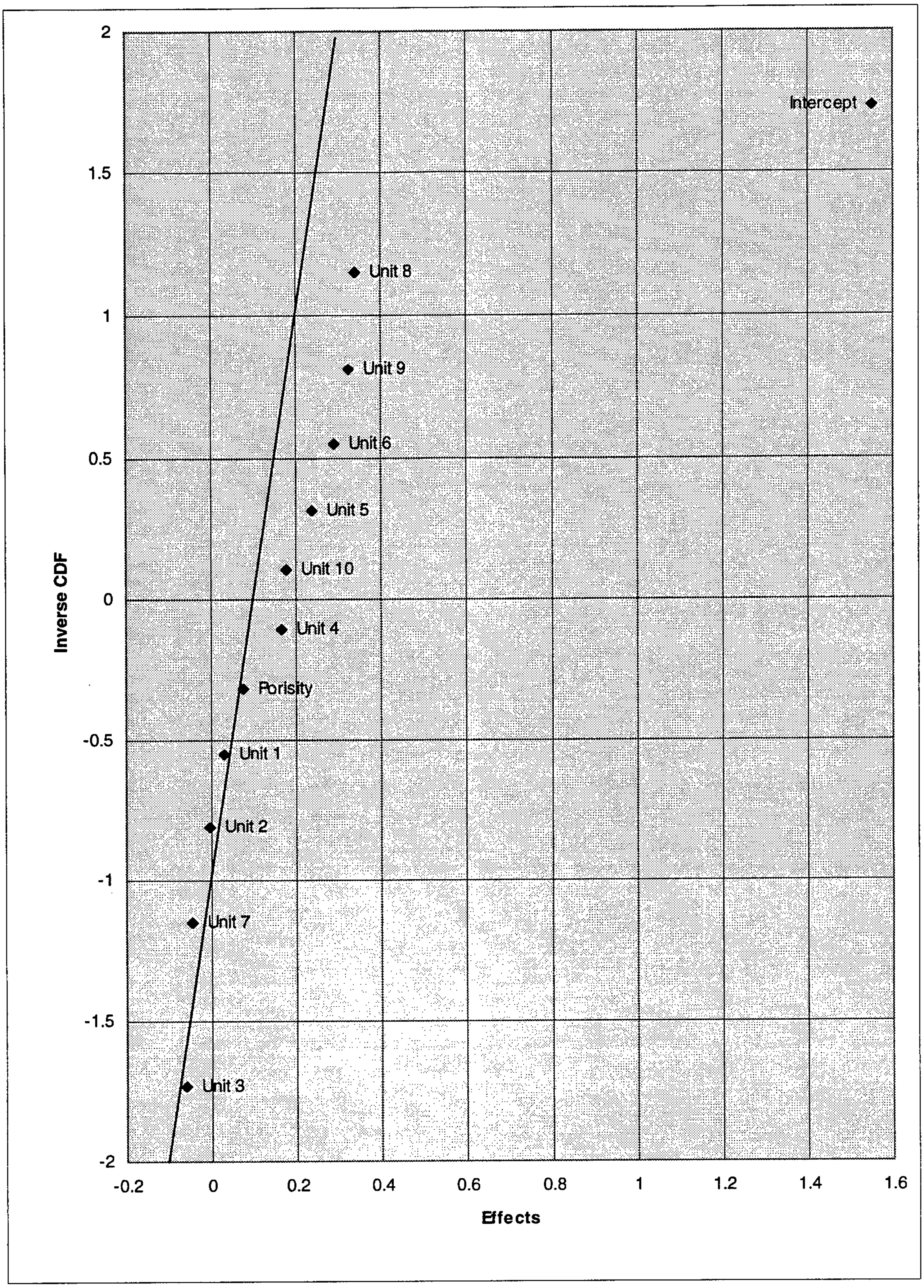

**Figure 3.9 Normal Probability Plot
Reduced Target Data Set**

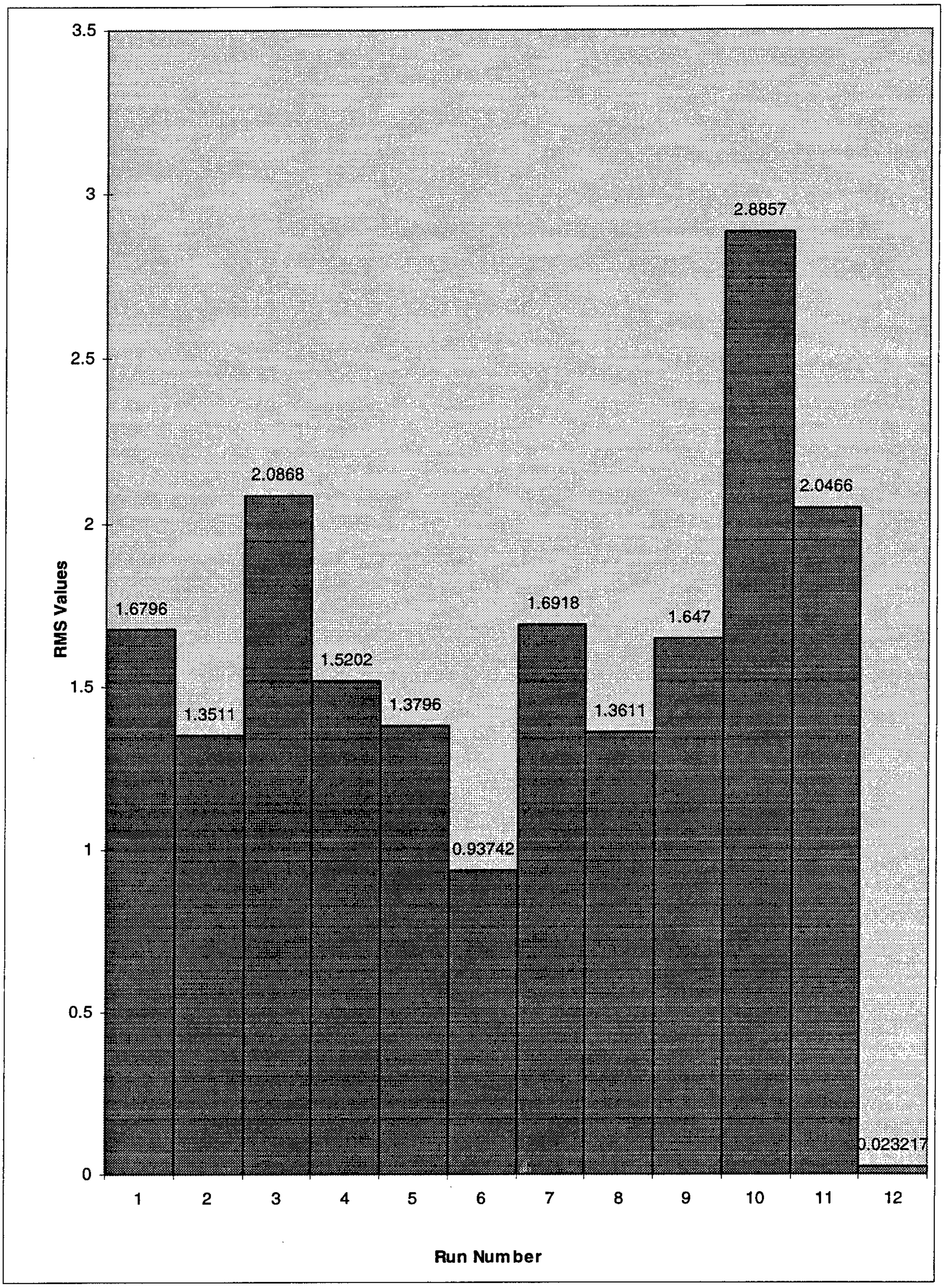

Figure 3.10 Screening Design RMS Values
Reduced Target Data Set

Design A

The settings for design A were the same settings used for design A in the full target data set calibration (Table 3.3). The results from the experimental design are summarized in Table 3.10, and the steepest descent vector computed from the RMS values is presented in Table 3.11.

Table 3.10 Design A Summary Statistics
Reduced Target Data Set

Run	SSE	RMS	MAE	ME
1	0.0059	0.0157	0.0119	-0.0078
2	0.0055	0.0152	0.0117	-0.0116
3	0.0378	0.0397	0.0260	-0.0076
4	0.0404	0.0410	0.0271	-0.0071
5	0.0343	0.0378	0.0246	-0.0151
6	0.0091	0.01943	0.0125	-0.0124
7	0.0087	0.0190	0.0123	-0.0112
8	0.0077	0.0179	0.0135	-0.0093
9	0.0086	0.0189	0.0138	-0.0117
10	0.0146	0.0247	0.0184	-0.0036
11	0.0077	0.0179	0.0129	-0.0056
12	0.0129	0.0232	0.0172	-0.0160

Table 3.11 Design A Steepest Descent Vector
Reduced Target Data Set

	Direction of Steepest Ascent	Direction of Steepest Descent	Steepest Descent Unit Vector
Porosity	0.0014	-0.0014	-0.1563
Unit1	0.0006	-0.0006	-0.0680
Unit2	0.0013	-0.0013	-0.1362
Unit 3	0.0008	-0.0008	-0.0836
Unit 4	0.0022	-0.0022	-0.2387
Unit 5	-0.0007	0.0007	0.0777
Unit 6	-0.0020	0.0020	0.2204
Unit 7	-0.0067	0.0067	0.7272
Unit 8	-0.0020	0.0020	0.2181
Unit 9	0.0019	-0.0019	-0.2007
Unit 10	0.0043	-0.0043	-0.4660

The results of the experiments conducted along the steepest descent gradient are illustrated in Figure 3.11. The response values obtained from the experiments stopped decreasing after 14 unit steps from the center of design region A. The RMS response value was reduced from the lowest value of design A (0.0232) to a value of 0.0031 at 14 unit steps away from the center of design A. Therefore, the parameter values for the experiment at step 14 were used in constructing design B.

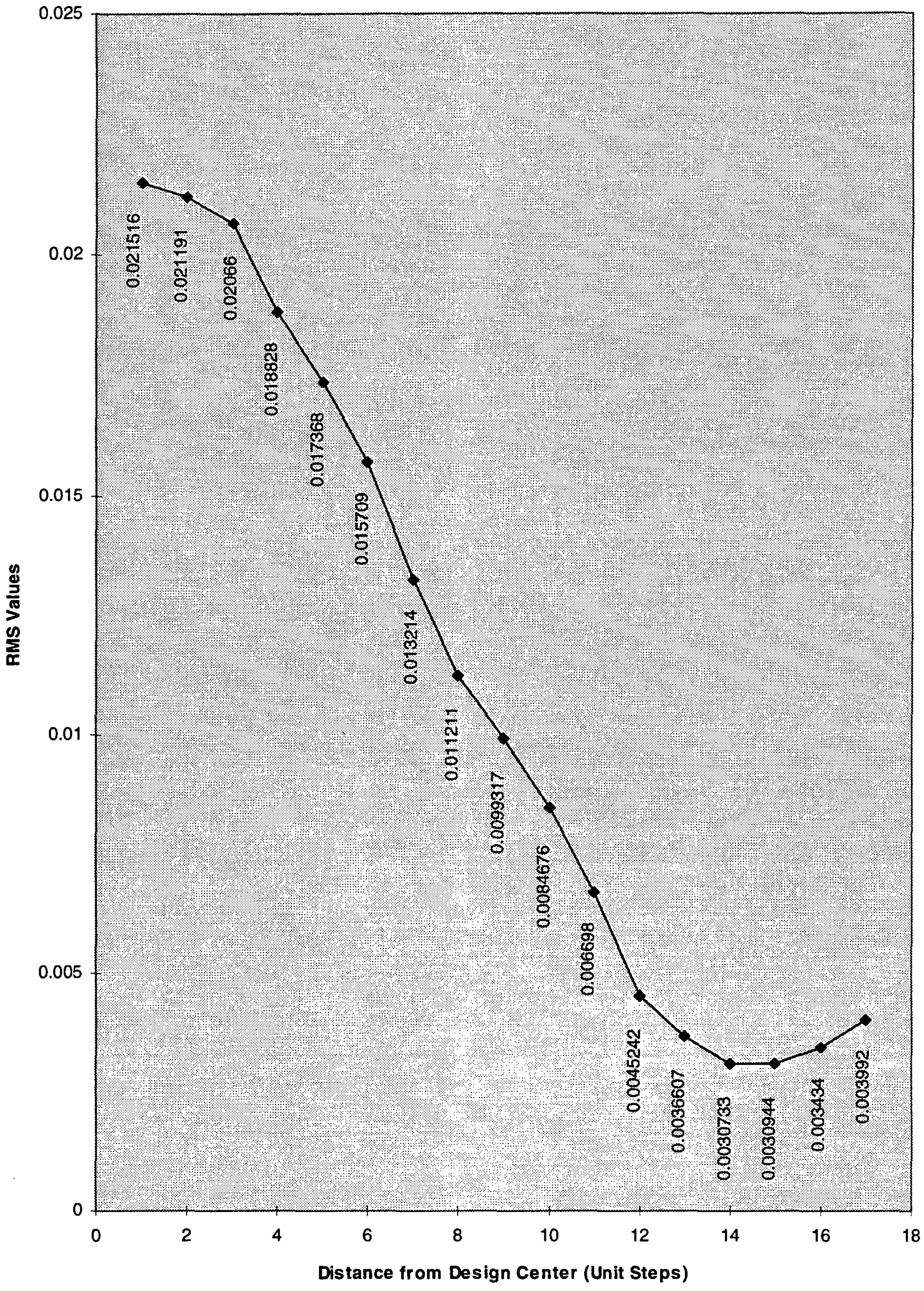

Figure 3.11 Design A Steepest Descent
Reduced Target Data Set

Design B

The parameter settings, response values, and steepest descent vector for design B are presented in Tables 3.12, 3.13, and 3.14 respectively.

Table 3.12 Design B Parameter Settings
Reduced Target Data Set

Parameter	Lower Bound	Upper Bound
Porosity	.06	.08
Unit 1	3.2761×10^{-5}	1.1276×10^{-4}
Unit 2	1.0000×10^{-6}	5.0000×10^{-6}
Unit 3	1.0000×10^{-6}	5.0000×10^{-6}
Unit 4	1.0000×10^{-6}	5.0000×10^{-6}
Unit 5	1.0000×10^{-6}	5.0000×10^{-6}
Unit 6	1.3042×10^{-5}	2.1042×10^{-5}
Unit 7	2.3864×10^{-6}	1.0386×10^{-5}
Unit 8	1.0000×10^{-7}	5.0000×10^{-7}
Unit 9	1.0000×10^{-7}	5.0000×10^{-7}
Unit 10	1.0000×10^{-7}	5.0000×10^{-7}

Table 3.13 Design B Summary Statistics
Reduced Target Data Set

Run	SSE	RMS	MAE	ME
1	0.0002	0.0027	0.0019	0.0015
2	0.0008	0.0057	0.0041	-0.0027
3	0.0054	0.0150	0.0098	-0.0088
4	0.0067	0.0167	0.0110	-0.0094
5	0.0075	0.0177	0.0131	-0.0114
6	0.0022	0.0095	0.0060	-0.0058
7	0.0025	0.0103	0.0064	-0.0063
8	0.0033	0.0118	0.0077	-0.0068
9	0.0008	0.0057	0.0043	-0.0013
10	0.0015	0.0080	0.0067	-0.0008
11	0.0028	0.0107	0.0063	0.0054
12	0.0035	0.0121	0.0081	-0.0080

Table 3.14 Design B Steepest Descent Vector
Reduced Target Data Set

	Direction of Steepest Ascent	Direction of Steepest Descent	Steepest Descent Unit Vector
Porosity	-0.0004	0.0004	0.1009
Unit1	0.0010	-0.0010	-0.2285
Unit2	0.0005	-0.0005	-0.1158
Unit 3	0.0008	-0.0008	-0.1869
Unit 4	0.0008	-0.0008	-0.1806
Unit 5	-0.0003	0.0003	0.0774
Unit 6	-0.0003	0.0003	0.0714
Unit 7	-0.0028	0.0028	0.6407
Unit 8	-0.0026	0.0026	0.5944
Unit 9	0.0008	-0.0008	-0.1906
Unit 10	0.0009	-0.0009	-0.2132

After 3 unit steps along the steepest descent path, the RMS response obtained (0.0032) was still greater than the lowest value obtained from design B, run 1 (0.0027), implying the first order model no longer provided an adequate approximation of the response surface. However, a second-order model was not deemed necessary due to the small value of RMS. Therefore, the parameters for run 1 from design B were considered the calibrated parameter values for reduced target data set calibration because they produced the lowest RMS response. The values are presented in Table 3.15.

Table 3.15 Calibrated Parameter Values Reduced Target Data Set

Parameter	Calibrated Value
Porosity	.08
Unit 1	3.2761 x 10^{-5}
Unit 2	5.0000 x 10^{-6}
Unit 3	1.0000 x 10^{-6}
Unit 4	1.0000 x 10^{-6}
Unit 5	1.0000 x 10^{-6}
Unit 6	2.1042 x 10^{-5}
Unit 7	1.0386 x 10^{-5}
Unit 8	5.0000 x 10^{-7}
Unit 9	1.0000 x 10^{-7}
Unit 10	5.0000 x 10^{-7}

Data enrichment techniques

In order to increase the size of the reduced target data set, several data enrichment techniques were evaluated. The techniques evaluated included kriging with exponential, linear, quadratic, and spherical variogram models and the inverse distance method to the first, second, and third powers. The different types of kriging used refer to the type of function that is used to obtain the **C** and **D** matrices described in Chapter 2. The estimated data values were created and compared to the full calibration target data set using the program *Surfer,* which automatically computed the residuals between the estimated and actual data sets for each data enrichment technique. The summary statistics for each methods are presented in Table 3.15. The actual residual values for each enriched data set are presented in Appendix C.

Table 3.16 Summary Statistics for Data Enrichment Techniques

	Kriging				Inverse Distance to a Power		
	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
SSE	2931.6897	722.0152	7159.5240	6202.3425	3967.8213	1596.7545	1593.2713
RMS	2.36533	1.1738	3.6964	3.4404261	2.7518	1.7456	1.7437
MAE	1.6382	0.8470	2.7877	2.4960	1.9597	1.3412	1.3660
ME	-0.7724	-0.473	-0.9763	-0.9620	-1.6687	-1.2262	-1.0477

The summary statistics obtained for the linear kriging technique are considerably smaller than the statistics for the other methods, indicating that linear kriging provides better estimates of hydraulic head values than any of the other methods. Therefore, linear kriging was used to create an enriched target data set, and this data set was used as the target data set in the final phase of the study.

Enriched Target Data Set Calibration

The final phase of the study involved a calibration using the enriched calibration target data set produced during the third phase. The enriched data set replaced the actual calibration target data set, and the error statistics computed after every SUTRA run were calculated based on a comparison with the enriched target data set.

As in the previous two calibrations, the first step in the process was to conduct a screening experiment with the dual goal of determining influential parameters and finding a suitable starting point for the first design. The parameter values and design used in this step were identical to those in the previous screening experiments (Tables 3.1 and 3.2). The RMS responses were used to create a normal probability plot (Figure 3.12), showing that the effects for units 5, 6, 7, and 8 influenced the response. However, the Plackett-Burman design was once again used in the design stages of the calibration process to prevent inadvertent screening of influential effects. A comparison of RMS values (Figure 3.13) for the screening design showed the minimum response was obtained at run 12, and the parameter values for this run were used to set up design A.

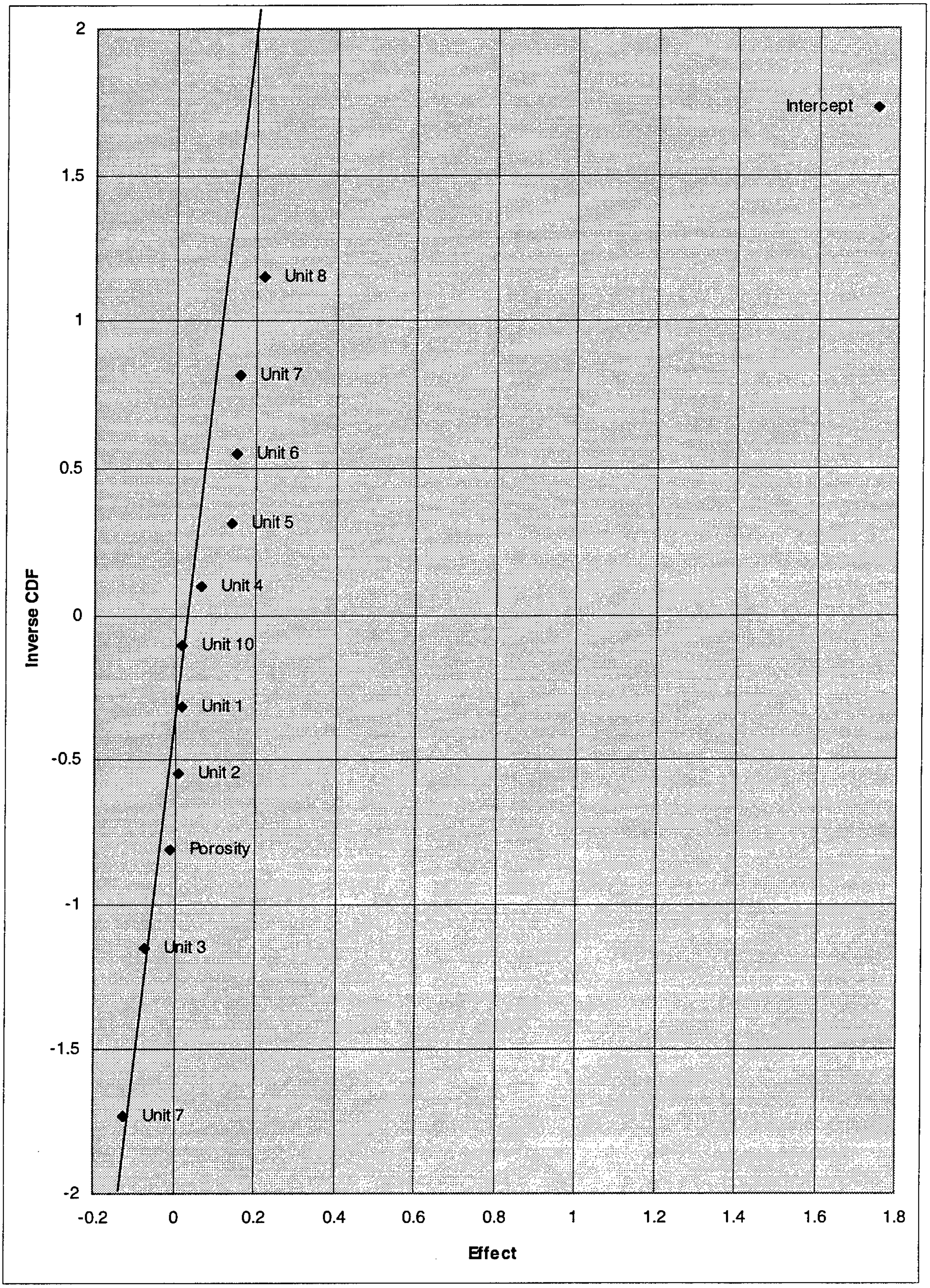

Figure 3.12 Normal Probability Plot
Enriched Target Data Set

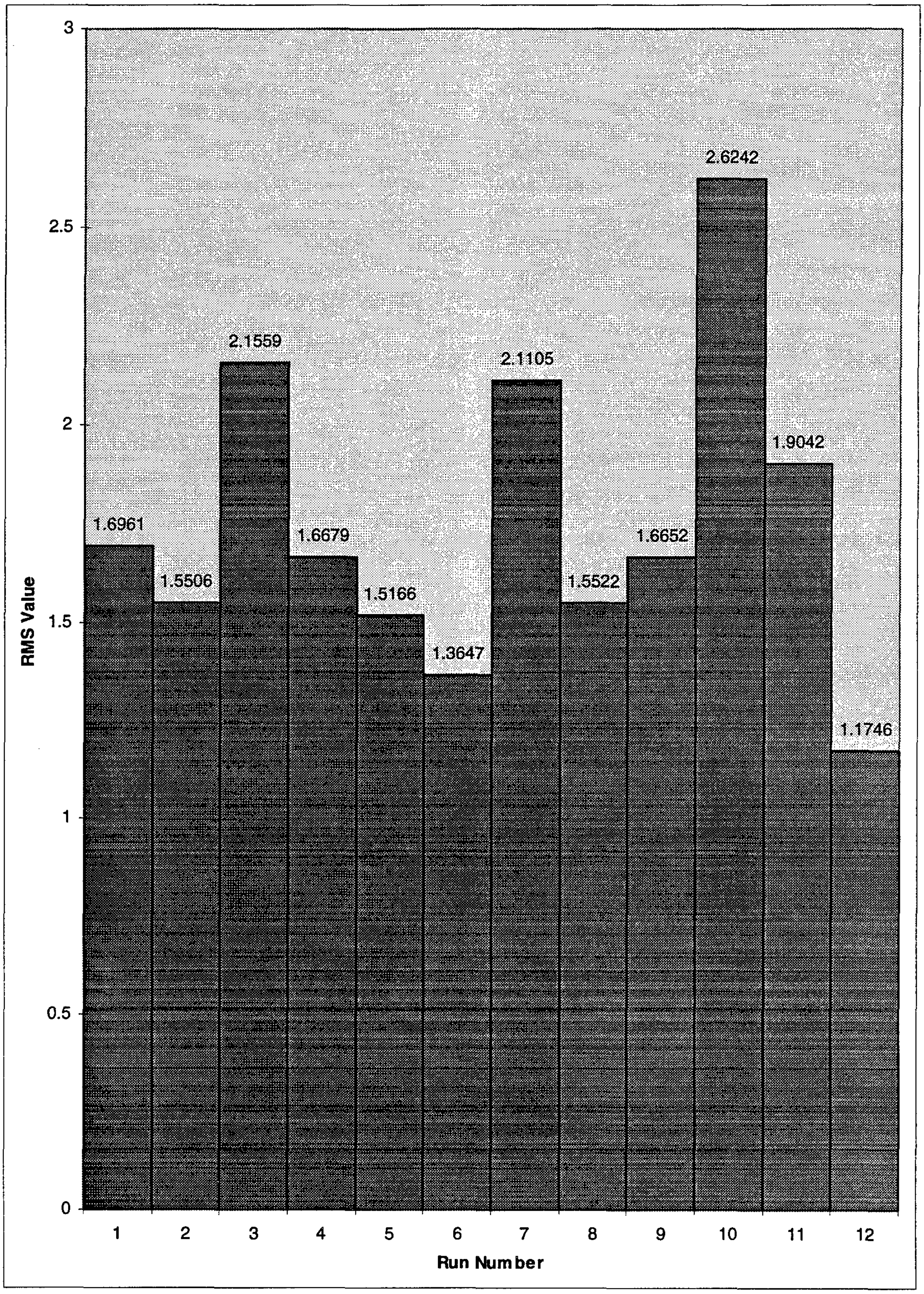

Figure 3.13 Screening Design RMS Values
Enriched Target Data Set

Design A

The settings used for design A were identical to the settings used in the first two calibration efforts (Table 3.3). The summary statistics from the experiments are shown in Table 3.17

Table 3.17 Design A Summary Statistics
Enriched Target Data Set

Run	SSE	RMS	MAE	ME
1	722.28	1.1741	0.8465	-0.4751
2	724.39	1.1758	0.8478	-0.4764
3	730.24	1.1805	0.8505	-0.4728
4	728.25	1.1789	0.8494	-0.4715
5	722.16	1.1740	0.8448	-0.4723
6	721.87	1.1737	0.8460	-0.4756
7	725.83	1.1769	0.8483	-0.4768
8	724.61	1.1759	0.8485	-0.4752
9	722.47	1.1742	0.8467	-0.4746
10	733.09	1.1828	0.8550	-0.4750
11	723.93	1.1754	0.8488	-0.4727
12	722.94	1.1746	0.8463	-0.4758

The results in the table for this screening experiment were considerably higher than the statistics obtained in the first two calibrations. These large values were caused by the inaccuracy of the enriched target data set. However, it was hoped that the enriched target data set would still provide an adequate calibration. The steepest descent direction obtained from the RMS responses in presented in Table 3.18.

Table 3.18 Design A Steepest Descent Vector Enriched Target Data Set

	Direction of Steepest Ascent	Direction of Steepest Descent	Steepest Descent Unit Vector
Porosity	0.0002	-0.0002	-0.0541
Unit1	-0.0004	0.0004	0.1262
Unit2	0.0003	-0.0003	-0.0962
Unit 3	-0.0005	0.0005	0.1623
Unit 4	0.0005	-0.0005	-0.1623
Unit 5	0.0006	-0.0006	-0.2103
Unit 6	0.0001	-0.0001	-0.0421
Unit 7	-0.0016	0.0016	0.5589
Unit 8	0.0010	-0.0010	-0.3546
Unit 9	0.0018	-0.0018	-0.6550
Unit 10	-0.0002	0.0002	0.0781

Figure 3.14 illustrates the behavior of the RMS responses along the steepest descent path. Figure 3.15 shows the behavior of the SSE statistic along the same path. Both charts are presented to better illustrate where the minimum response value lies. The RMS values flatten out after the fourth step and changes in response can no longer be discerned, but the SSE values continue to decrease until step 6. Therefore, the parameter values for step 6 were used to set up design B.

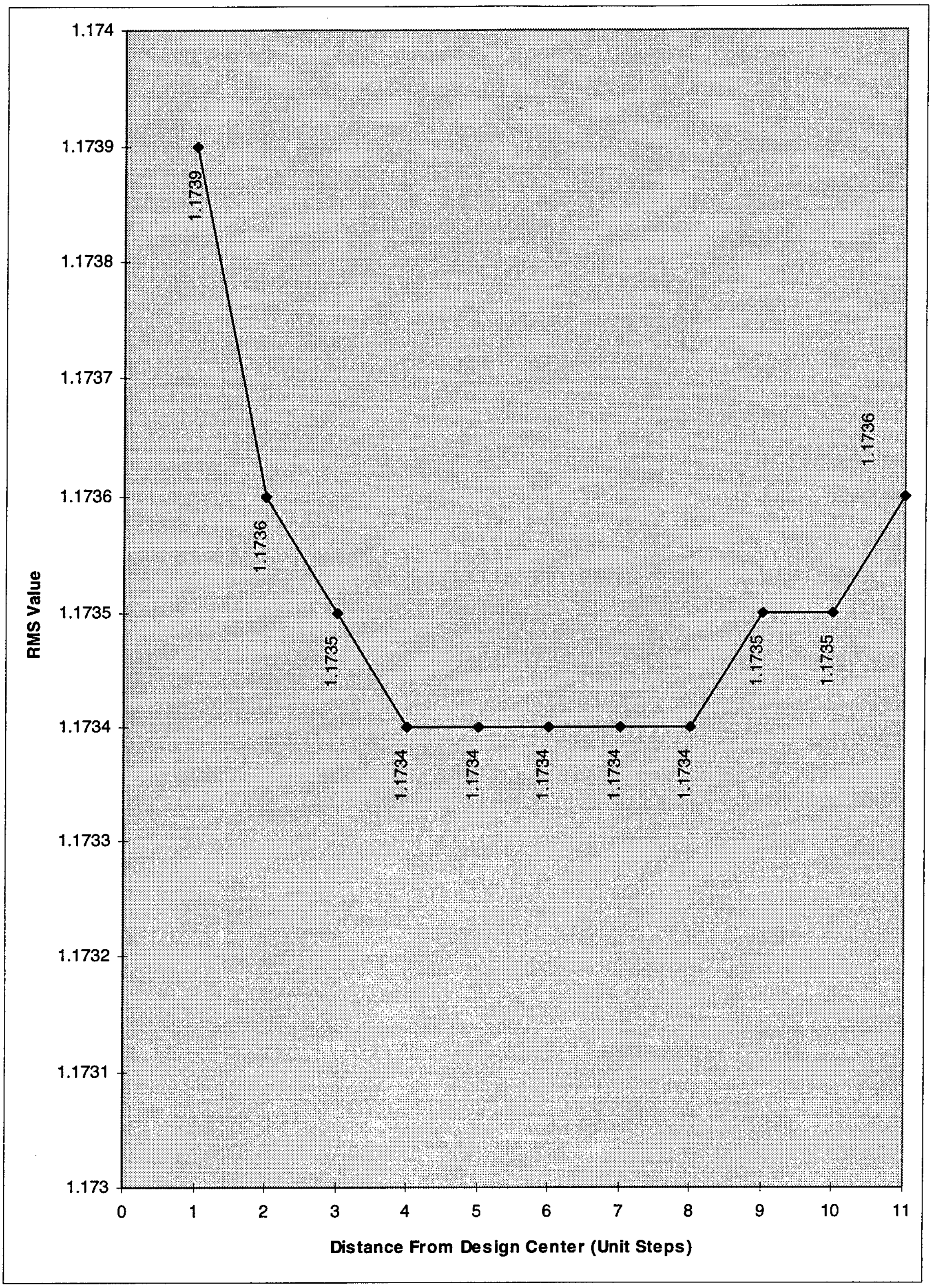

Figure 3.14 Design A Steepest RMS Descent
Enriched Target Data Set

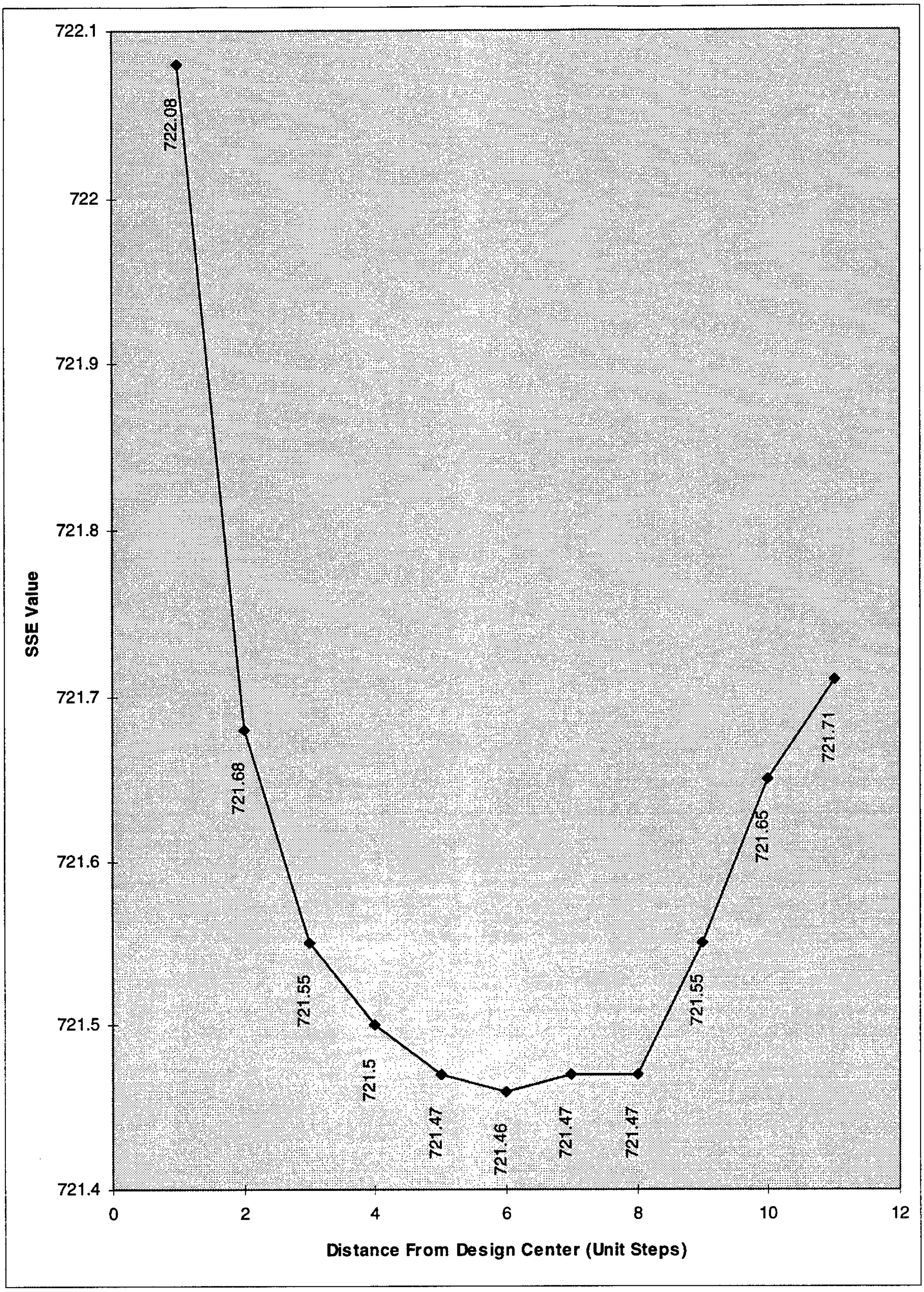

Figure 3.15 Design A SSE Descent
Enriched Target Data Set

Design B

The parameter settings, response values, and steepest descent vector for design B are presented in Tables 3.19, 3.20, and 3.21 respectively

Table 3.19 Design B Parameter Settings
Enriched Target Data Set

Parameter	Lower Bound	Upper Bound
Porosity	.06	.10
Unit 1	4.5336×10^{-5}	1.2534×10^{-4}
Unit 2	1.0000×10^{-6}	3.6154×10^{-6}
Unit 3	5.5432×10^{-6}	1.3543×10^{-5}
Unit 4	1.0000×10^{-6}	5.0000×10^{-6}
Unit 5	1.0000×10^{-6}	5.0000×10^{-6}
Unit 6	1.0000×10^{-6}	6.6442×10^{-6}
Unit 7	1.6649×10^{-6}	2.4649×10^{-6}
Unit 8	1.0000×10^{-7}	5.0000×10^{-7}
Unit 9	1.0000×10^{-7}	5.0000×10^{-7}
Unit 10	3.1875×10^{-7}	1.1875×10^{-6}

Table 3.20 Design B Summary Statistics
Enriched Target Data Set

Run	SSE	RMS	MAE	ME
1	721.66	1.1735	0.8457	-0.4759
2	722.37	1.1741	0.8469	-0.4753
3	721.96	1.1738	0.8456	-0.4760
4	722.04	1.1739	0.8461	-0.4750
5	721.88	1.1737	0.8459	-0.4750
6	721.44	1.1734	0.8456	-0.4757
7	721.65	1.1735	0.8453	-0.4767
8	722.18	1.1740	0.8464	-0.4752
9	722.04	1.1739	0.8464	-0.4751
10	722.78	1.1745	0.8473	-0.4751
11	722.35	1.1741	0.8470	-0.4742
12	721.61	1.1735	0.8458	-0.4757

Table 3.21 Design B Steepest Descent Vector Enriched Data Set

	Direction of Steepest Ascent	Direction of Steepest Descent	Steepest Descent Unit Vector
Porosity	0.00003	-0.00003	-0.0803
Unit1	-0.00006	0.00006	0.1874
Unit2	-0.00014	0.00014	0.4552
Unit 3	0.00003	-0.00003	-0.0803
Unit 4	0.00006	-0.00006	-0.1874
Unit 5	0.00006	-0.00006	-0.1874
Unit 6	0.00006	-0.00006	-0.1874
Unit 7	0.00001	-0.00001	-0.0268
Unit 8	0.00006	-0.00006	-0.1874
Unit 9	0.00024	-0.00024	-0.7764
Unit 10	-0.00001	0.00001	0.0268

The behavior of the RMS and SSE responses along the steepest descent path are depicted in Figures 3.16 and 3.17. The RMS value stopped decreasing after step 4 and the SSE response increased after step 11. Therefore, the parameters for step 11 were used to construct design C.

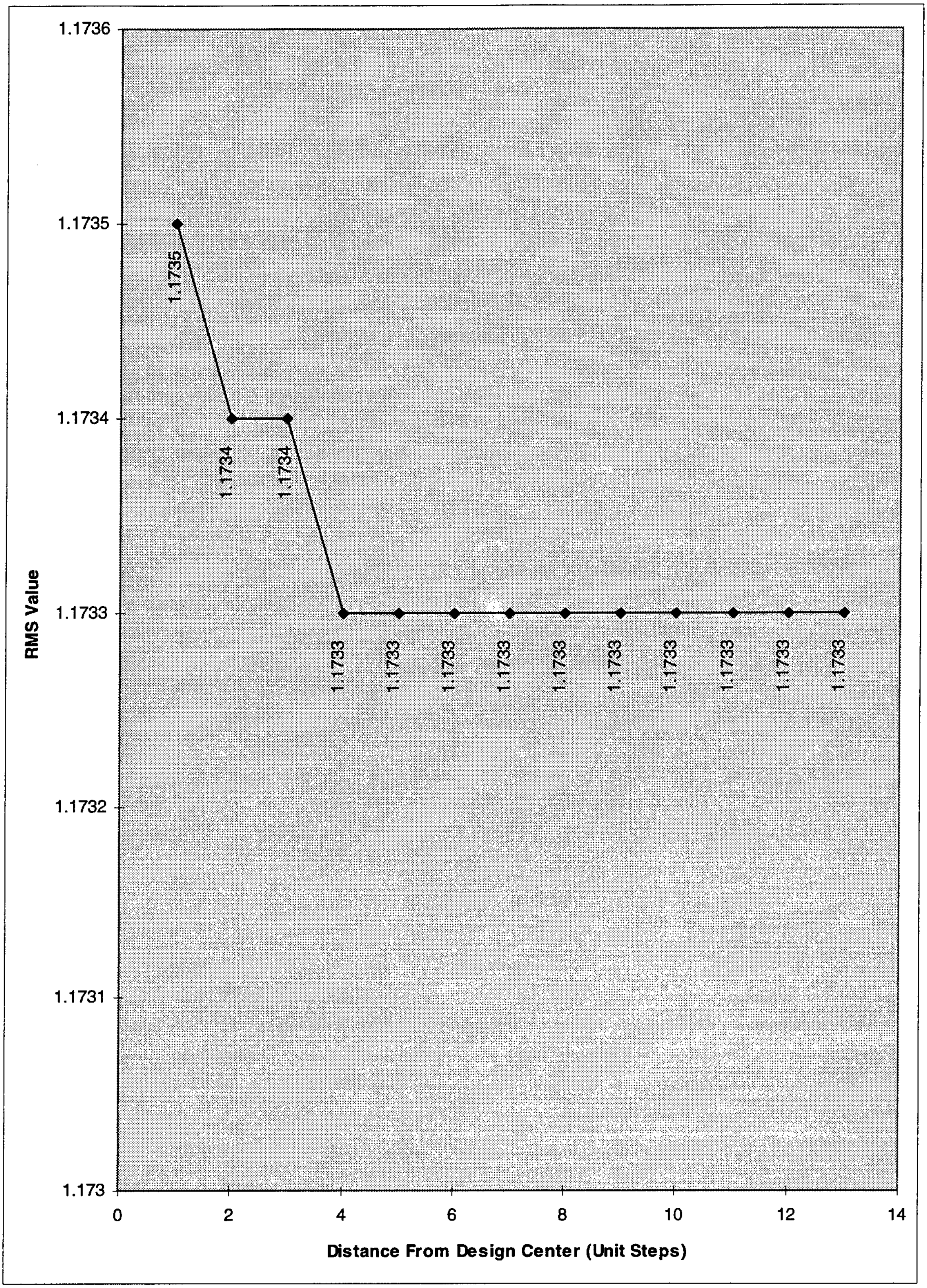

Figure 3.16 Design B Steepest RMS Descent
Enriched Target Data Set

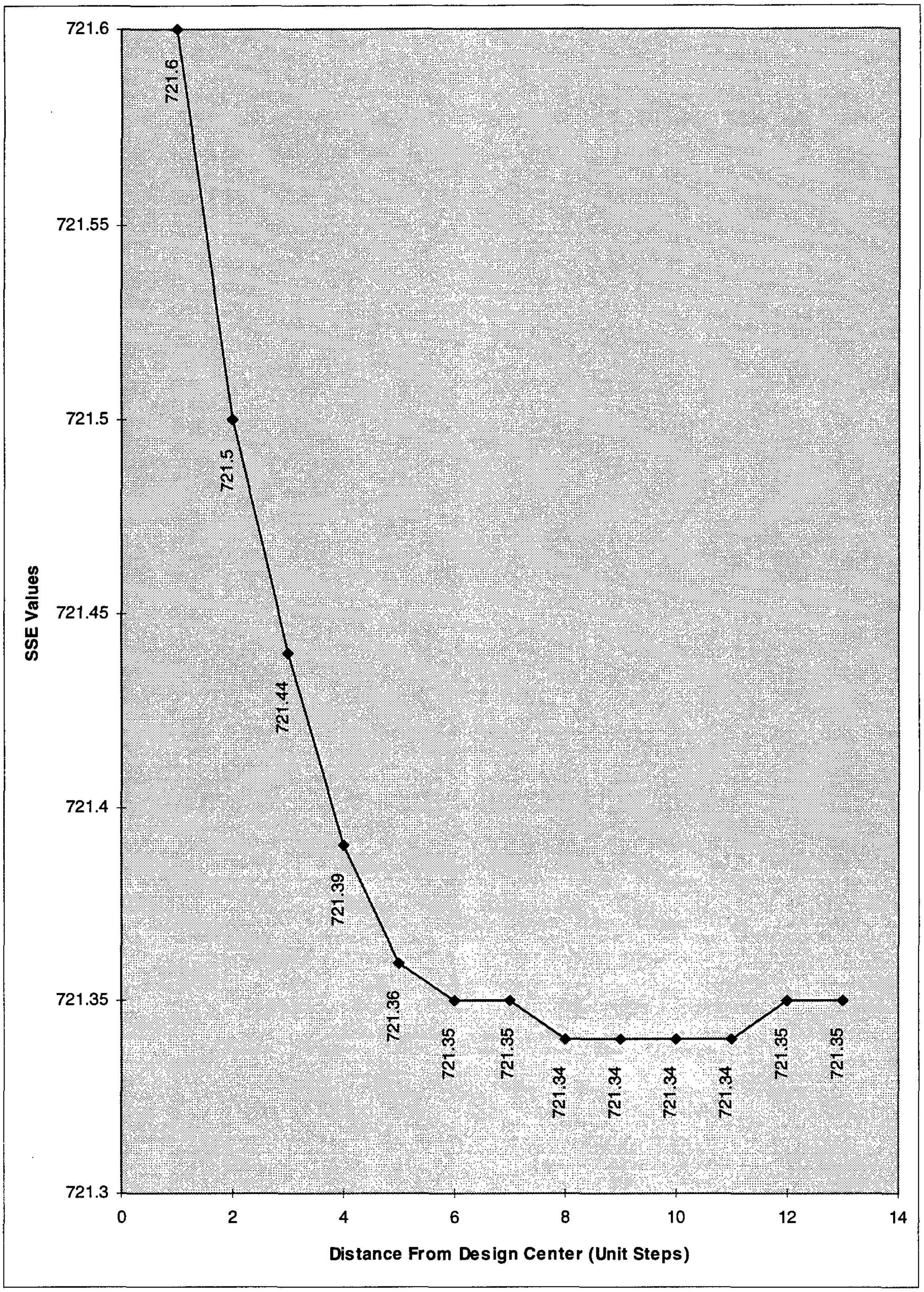

Figure 3.17 Design B SSE Descent
Enriched Target Data Set

Design C

The parameter settings, response values, and steepest descent vector for design C are presented in Tables 3.22, 3.23, and 3.24 respectively.

Table 3.22 Design C Parameter Settings
Enriched Target Data Set

Parameter	Lower Bound	Upper Bound
Porosity	.06	.08
Unit 1	1.0531×10^{-4}	1.8531×10^{-4}
Unit 2	9.8790×10^{-6}	1.8790×10^{-6}
Unit 3	3.6155×10^{-6}	1.1616×10^{-5}
Unit 4	1.0000×10^{-6}	5.0000×10^{-6}
Unit 5	1.0000×10^{-6}	5.0000×10^{-6}
Unit 6	1.0000×10^{-6}	5.0000×10^{-6}
Unit 7	1.5792×10^{-6}	2.3792×10^{-6}
Unit 8	1.0000×10^{-7}	5.0000×10^{-7}
Unit 9	1.0000×10^{-7}	5.0000×10^{-7}
Unit 10	4.0443×10^{-7}	1.2044×10^{-6}

Table 3.23 Design C Summary Statistics
Enriched Target Data Set

Run	SSE	RMS	MAE	ME
1	721.6	1.1735	0.8455	-0.4760
2	722.08	1.1739	0.8461	-0.4760
3	721.91	1.1738	0.8455	-0.4760
4	721.96	1.1738	0.8458	-0.4752
5	721.58	1.1735	0.8452	-0.4756
6	721.4	1.1733	0.8454	-0.4758
7	721.54	1.1735	0.8450	-0.4769
8	722.01	1.1738	0.8461	-0.4755
9	721.77	1.1736	0.8458	-0.4757
10	722.44	1.1742	0.8466	-0.4756
11	722.13	1.1739	0.8465	-0.4746
12	721.51	1.1734	0.8455	-0.4759

Table 3.24 Design C Steepest Descent Vector
Enriched Target Data Set

	Direction of Steepest Ascent	Direction of Steepest Descent	Steepest Descent Unit Vector
Porosity	0.00002	-0.00002	-0.0673
Unit1	-0.00003	0.00003	0.1345
Unit2	-0.00007	0.00007	0.2691
Unit 3	1.9×10^{-17}	-1.9×10^{-17}	-7.5×10^{-14}
Unit 4	0.00002	-0.00002	-0.0673
Unit 5	0.00003	-0.00003	-0.1345
Unit 6	0.00005	-0.00005	-0.2018
Unit 7	-0.00002	0.00002	0.0673
Unit 8	0.00007	-0.00007	-0.2691
Unit 9	0.00022	-0.00022	-0.8745
Unit 10	-3.7×10^{-17}	3.7×10^{-17}	1.5×10^{-13}

After 3 steps, experiments conducted along the steepest descent path had not produced a response smaller than the lowest value obtained from design C (run 6). Therefore, the steepest descent method and the calibration process were halted. The parameters used in run 6 of design C were considered the calibrated parameter values. The values are summarized in Table 3.25.

Table 3.25 Calibrated Parameter Values
Enriched Target Data Set

Parameter	Calibrated Value
Porosity	.08
Unit 1	1.8531×10^{-4}
Unit 2	9.8790×10^{-6}
Unit 3	3.6155×10^{-6}
Unit 4	5.0000×10^{-6}
Unit 5	5.0000×10^{-6}
Unit 6	1.0000×10^{-6}
Unit 7	2.3792×10^{-6}
Unit 8	1.0000×10^{-7}
Unit 9	1.0000×10^{-7}
Unit 10	4.0443×10^{-7}

Comparison of Results

The calibrated parameter values from the three calibrations completed in this study and the calibrations done by Cotman (1995) and Smith and Ritzi (1993) are presented in Table 3.26.

Table 3.26 Calibrated Parameter Values

Parameter	Full Target Data Set	Reduced Target Data Set	Enriched Target Data Set	Cotman	Smith-Ritzi
Porosity	.07	.08	.08	.10	.11
Unit 1	8.3731×10^{-5}	3.2761×10^{-5}	1.8531×10^{-4}	5.0000×10^{-3}	2.0000×10^{-3}
Unit 2	2.9358×10^{-6}	5.0000×10^{-6}	9.8790×10^{-6}	9.8430×10^{-3}	1.0000×10^{-3}
Unit 3	1.0000×10^{-6}	1.0000×10^{-6}	3.6155×10^{-6}	5.0000×10^{-3}	1.0000×10^{-4}
Unit 4	1.0000×10^{-6}	1.0000×10^{-6}	5.0000×10^{-6}	5.0000×10^{-3}	3.0000×10^{-5}
Unit 5	2.1704×10^{-6}	1.0000×10^{-6}	5.0000×10^{-6}	5.0000×10^{-3}	2.0000×10^{-3}
Unit 6	1.6759×10^{-5}	2.1042×10^{-5}	1.0000×10^{-6}	1.0090×10^{-1}	3.0000×10^{-4}
Unit 7	1.0635×10^{-5}	1.0386×10^{-5}	2.3792×10^{-6}	5.0000×10^{-3}	6.0000×10^{-4}
Unit 8	2.2655×10^{-7}	5.0000×10^{-7}	1.0000×10^{-7}	5.0000×10^{-3}	6.0000×10^{-6}
Unit 9	2.0786×10^{-7}	1.0000×10^{-7}	1.0000×10^{-7}	4.3850×10^{-8}	4.0000×10^{-6}
Unit 10	2.8542×10^{-7}	5.0000×10^{-7}	4.0443×10^{-7}	1.4000×10^{-7}	1.0000×10^{-5}

The calibrated parameter values obtained from the three calibrations in this study were not similar to those of Cotman and Smith-Ritzi. It was felt this difference was caused by the nonuniqueness property exhibited by many inverse problems. However, even though the parameter values from the three calibration efforts did not match the previously calibrated models by Cotman and by Smith and Ritzi, the models calibrated in this study using the full and reduced target sets did produce parameter values which were close to one another. This result was promising because it indicated that reducing the number of nodes in the calibration target data set did not hinder the calibration effort. The calibrated parameter values from the enriched target data set calibration did not match the other two sets of calibrated parameter values, but the enriched data set calibration would not be needed if the calibration using the reduced target data set produced suitable results. Also, all three calibrations produced final calibrated parameters within the feasible range as defined by the parameter bounds.

Next, the accuracy of the three calibration efforts was compared to each other and to the results obtained by Cotman (1995). In order to provide a similar frame of reference, the error

Next, the accuracy of the three calibration efforts was compared to each other and to the results obtained by Cotman (1995). In order to provide a similar frame of reference, the error statistics in this section were computed using the full target data set. Therefore, the statistics differed from the results presented during calibration. Table 3.27 presents a comparison of the summary statistics for the best runs from each of the three calibration efforts with the results obtained by Cotman.

Table 3.27 Measures of Calibration Precision

Summary Statistics	Full Target Data Set	Reduced Target Data Set	Enriched Target Data Set	Cotman's Values
SSE	0.0244	0.0341	0.1724	0.0982
RMS	0.0068	0.0081	0.0181	0.0137
MAE	0.0027	0.0036	0.0093	0.0167
ME	0.0008	0.0007	-0.0023	0.0015
Maximum AE	0.0510	0.0490	0.0935	0.0757

The values in the table above indicate that each calibration produced a close match between the calibrated head values and the calibration target data set. The heads produced by the full and reduced target data set calibrations match the actual head values better than the calibration effort using the enriched target data set, once again indicating that the third calibration effort was unnecessary. The results obtained by Cotman fall between the reduced and enriched calibrations in accuracy. Figures 3.18-3.20 plot the best computed hydraulic head values from each calibration attempt versus the calibration target set of heads. The data plot along a 45 degree line, indicating a close match between the calibrated and actual head values for all three calibrations. Figures 3.21-3.23 plot the calibrated head errors versus horizontal position of the nodes. Figures 3.24-3.26 plot the calibrated head errors versus vertical position of the nodes. These six plots show the errors are randomly distributed over almost all of the nodes, indicating the SUTRA model has been evenly calibrated, without concentrating errors in any particular area of the groundwater system.

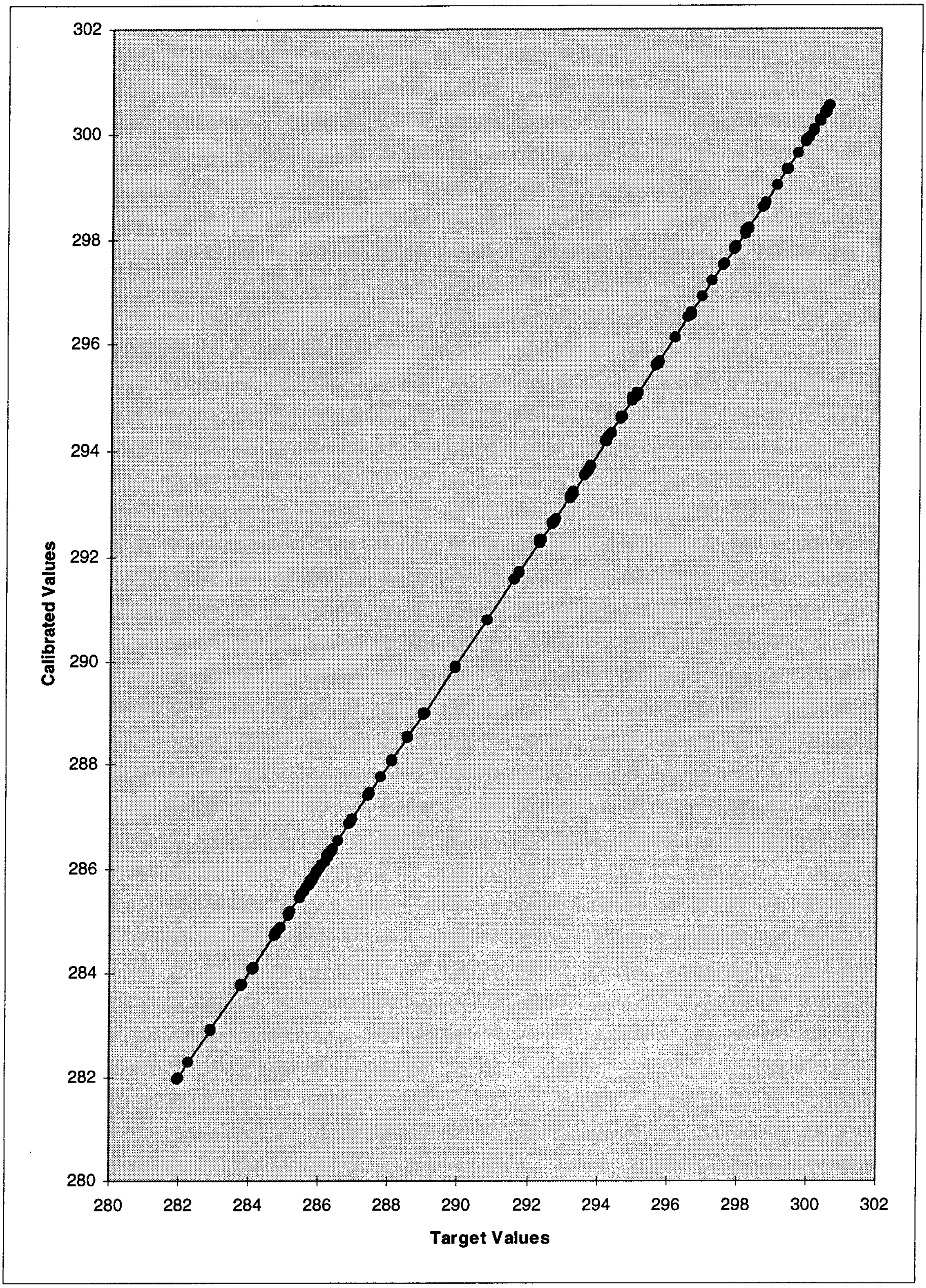

Figure 3.18 Calibrated vs. Actual Heads
Full Target Data Set

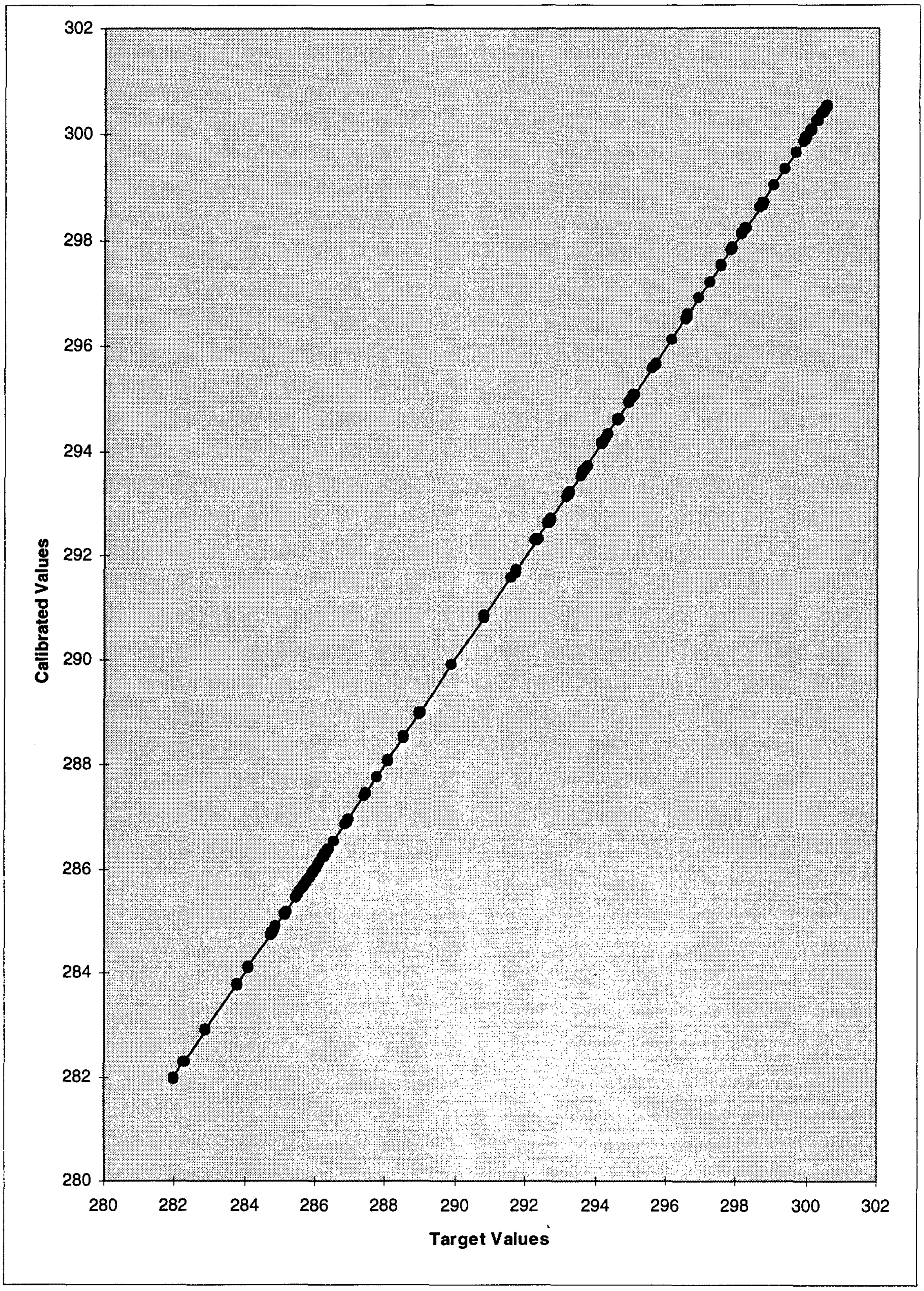

Figure 3.19 Calibrated vs. Actual Heads
Reduced Target Data Set

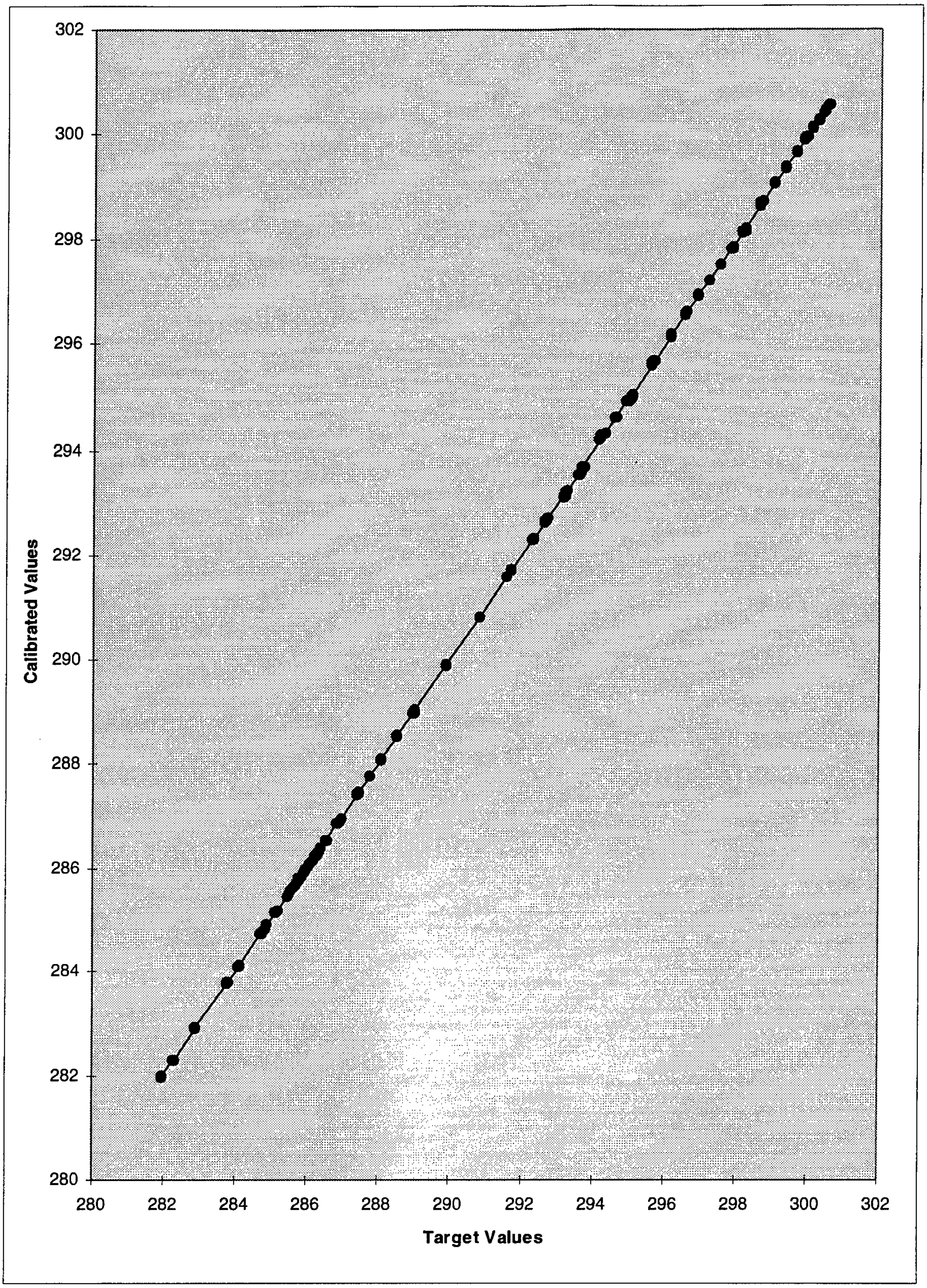

Figure 3.20 Calibrated vs. Actual Heads
Enriched Target Data Set

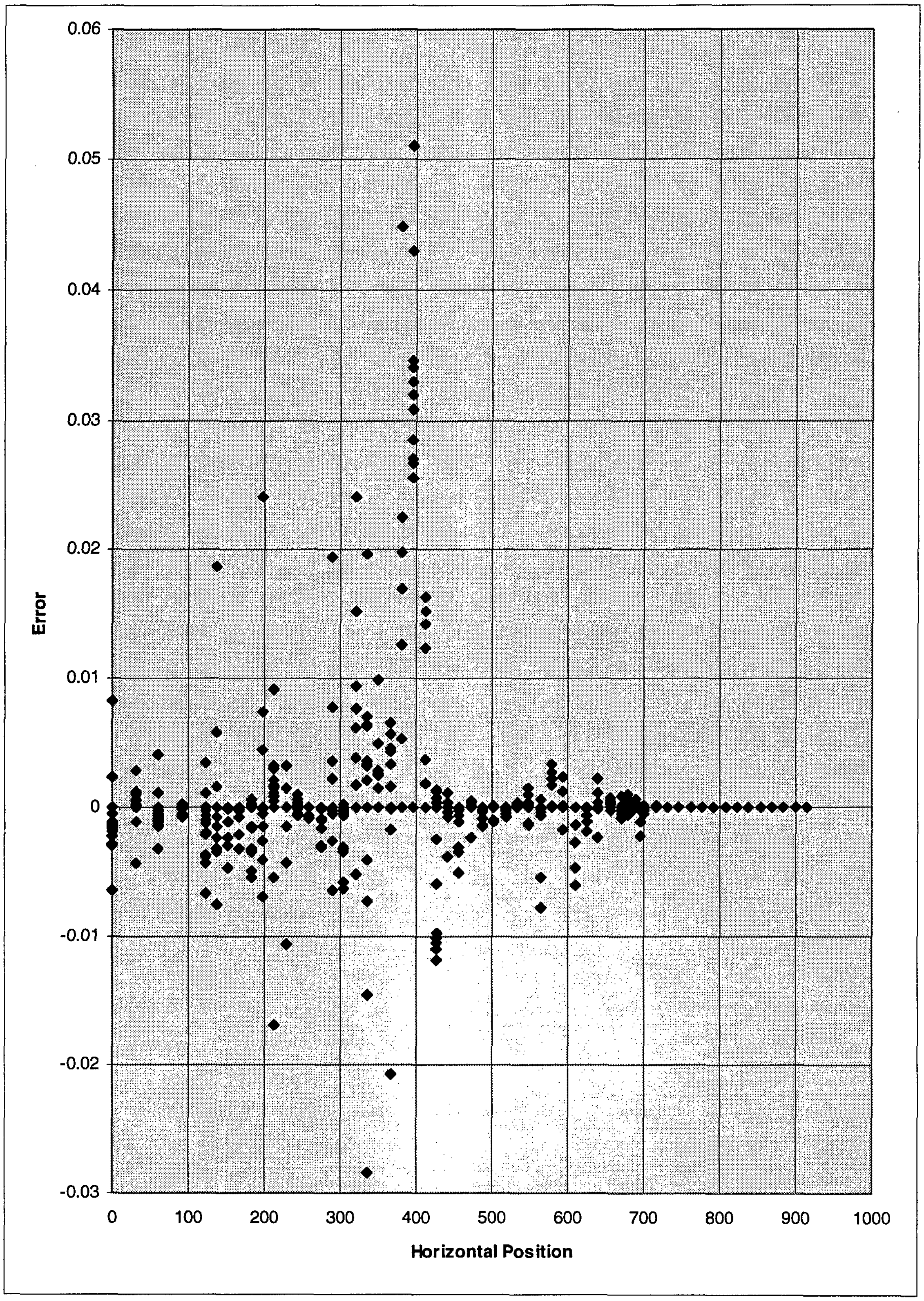

Figure 3.21 Error vs. Horizontal Position
Full Target Data Set

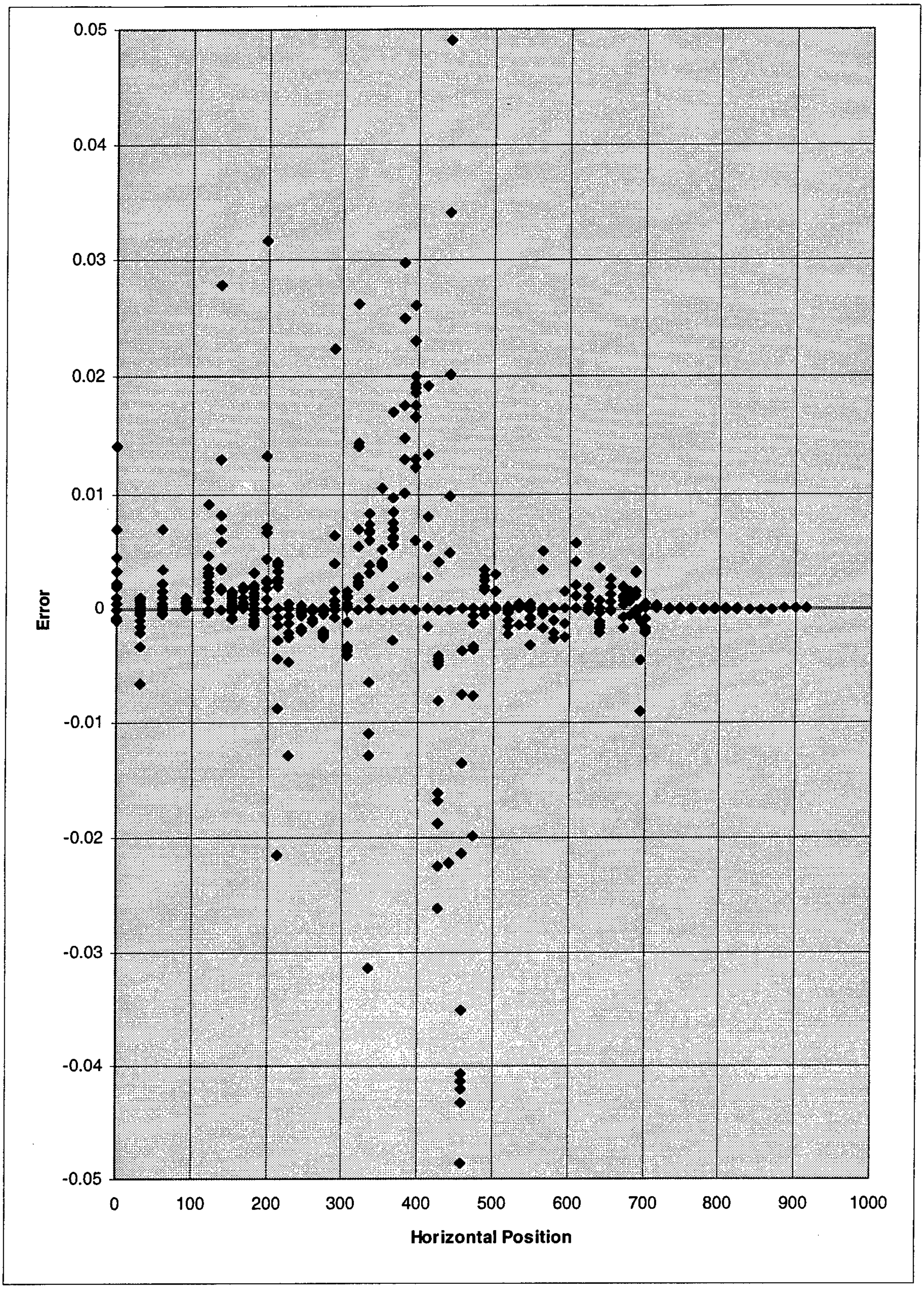

**Figure 3.22 Error vs. Horizontal Position
Reduced Target Data Set**

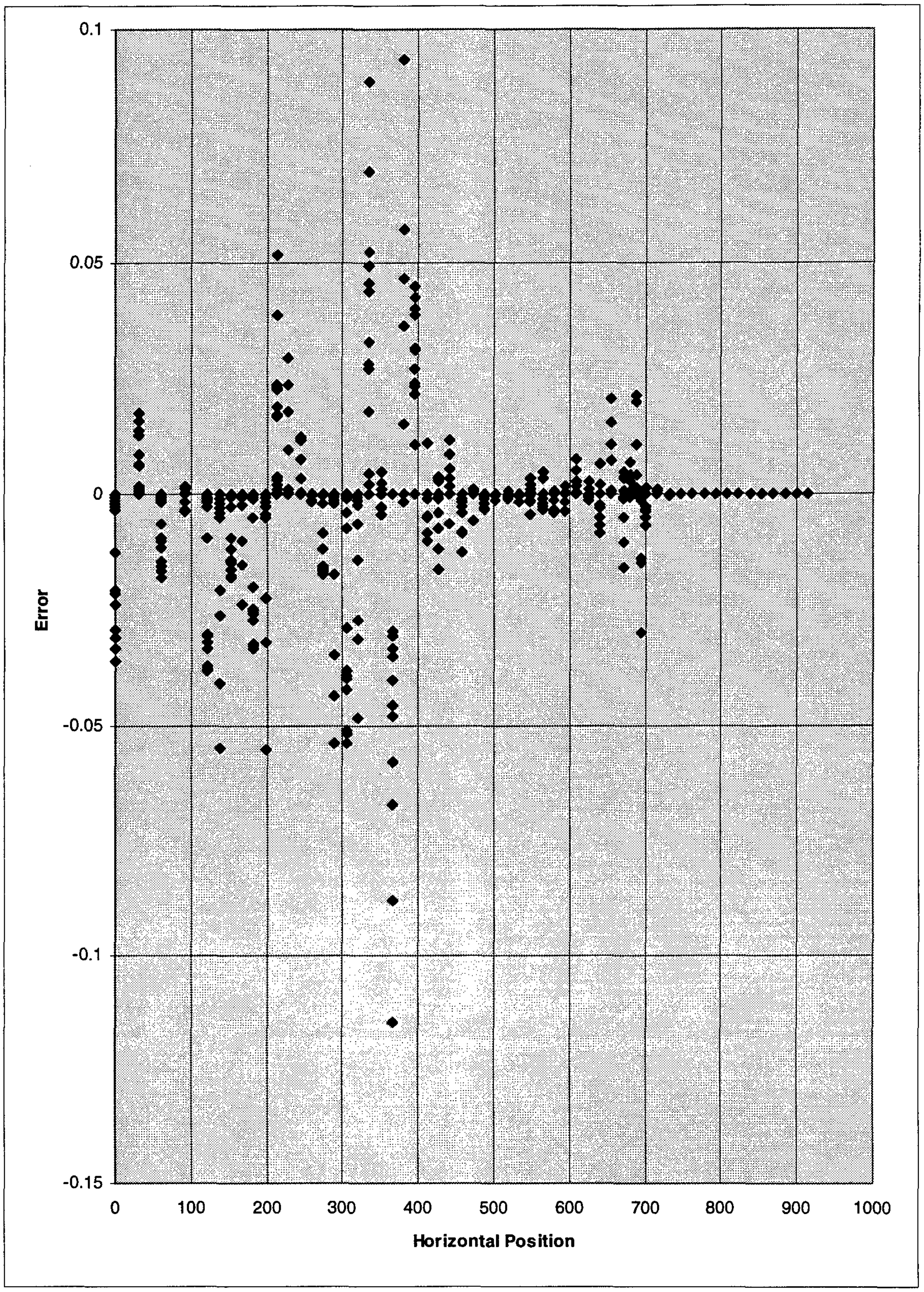

Figure 3.23 Error vs. Horizontal Position
Enriched Target Data Set

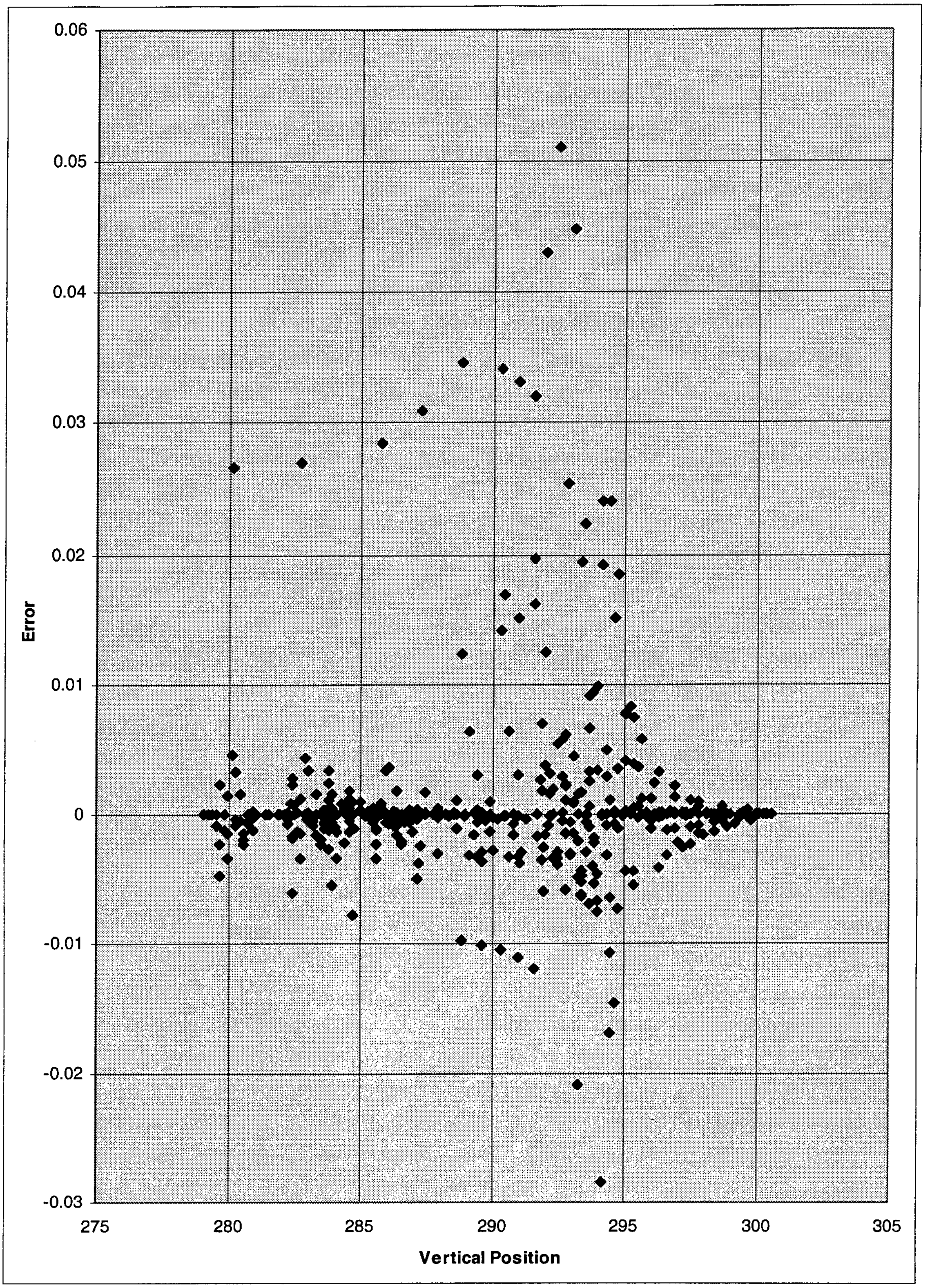

Figure 3.24 Error vs. Vertical Position
Full Target Data Set

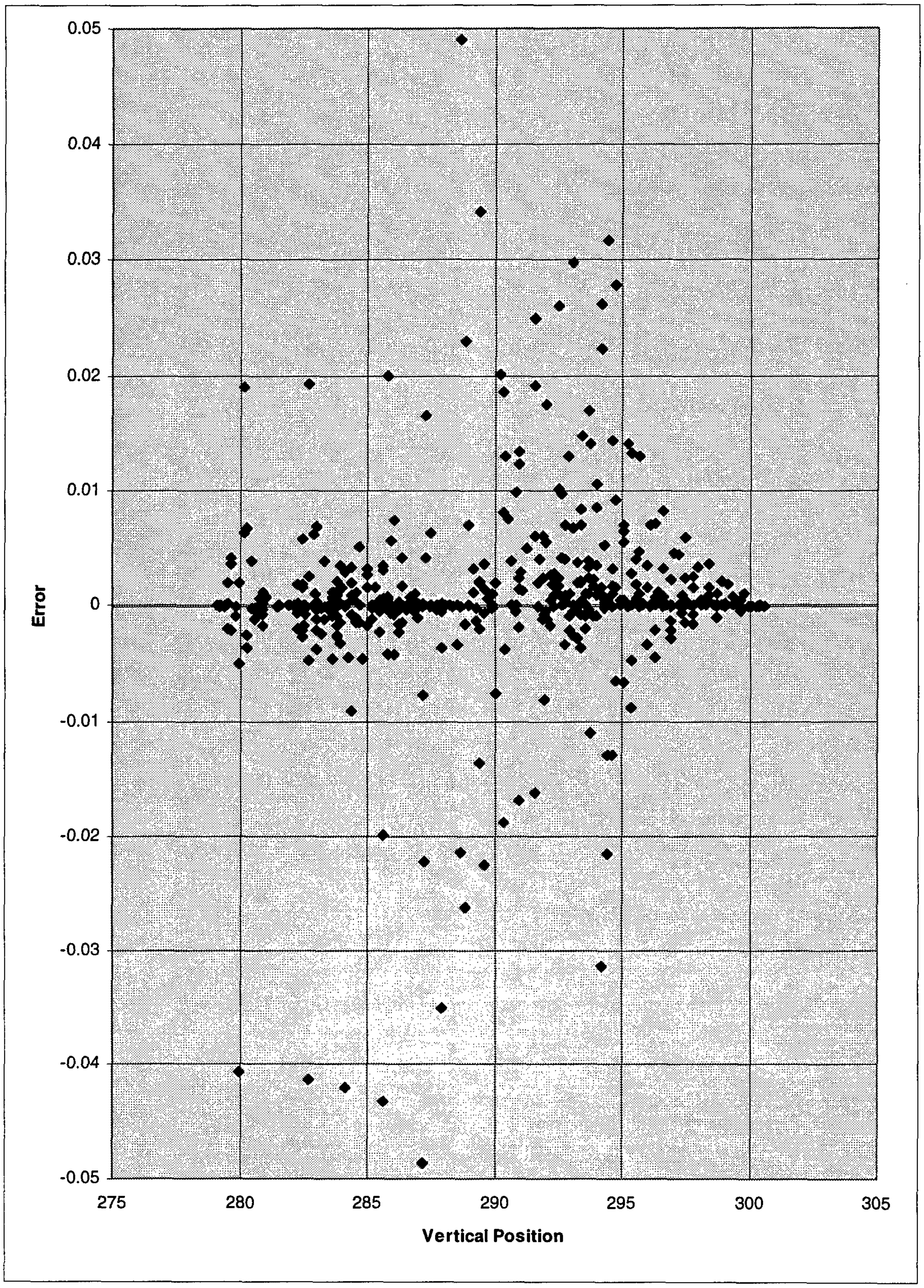

Figure 3.25 Error vs. Vertical Position
Reduced Target Data Set

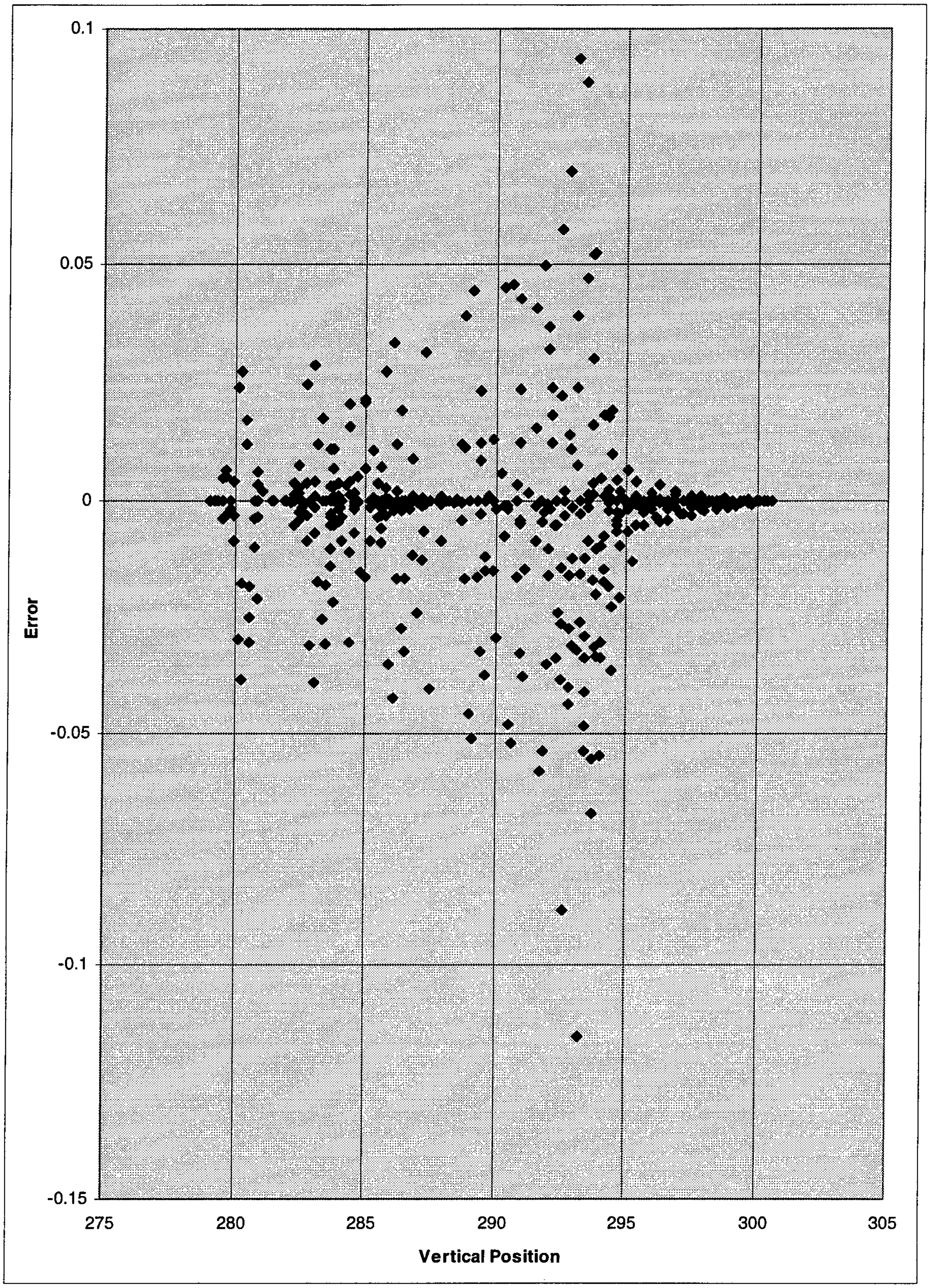

**Figure 3.26 Error vs. Vertical Position
Enriched Target Data Set**

Figure 3.27 plots the best RMS response values from each design and gradient search for each of the three calibrations. The values in the graph are obtained through a comparison with the actual complete data set. The plot shows that even though the RMS values appeared to be decreasing during the third calibration, in actuality the responses were increasing after the gradient search for design A. This phenomenon was caused by the fact that during the calibration, the responses were being computed based on an estimated target data set, instead of the actual target data values. Once again it was apparent that the enriched target data set calibration did not offer as good a calibration as the other two methods.

Although the RSM technique produced very good calibrated models, the final values of the input parameters do not match the values used in the Smith-Ritzi model even though they are feasible. However, the RSM technique did show that similar calibrated parameter values could be obtained even if the size of the data set was reduced. The technique also showed that the use of data enrichment techniques did not improve the calibration effort using the reduced target data set for this specific study, but that it still provided an accurate calibration.

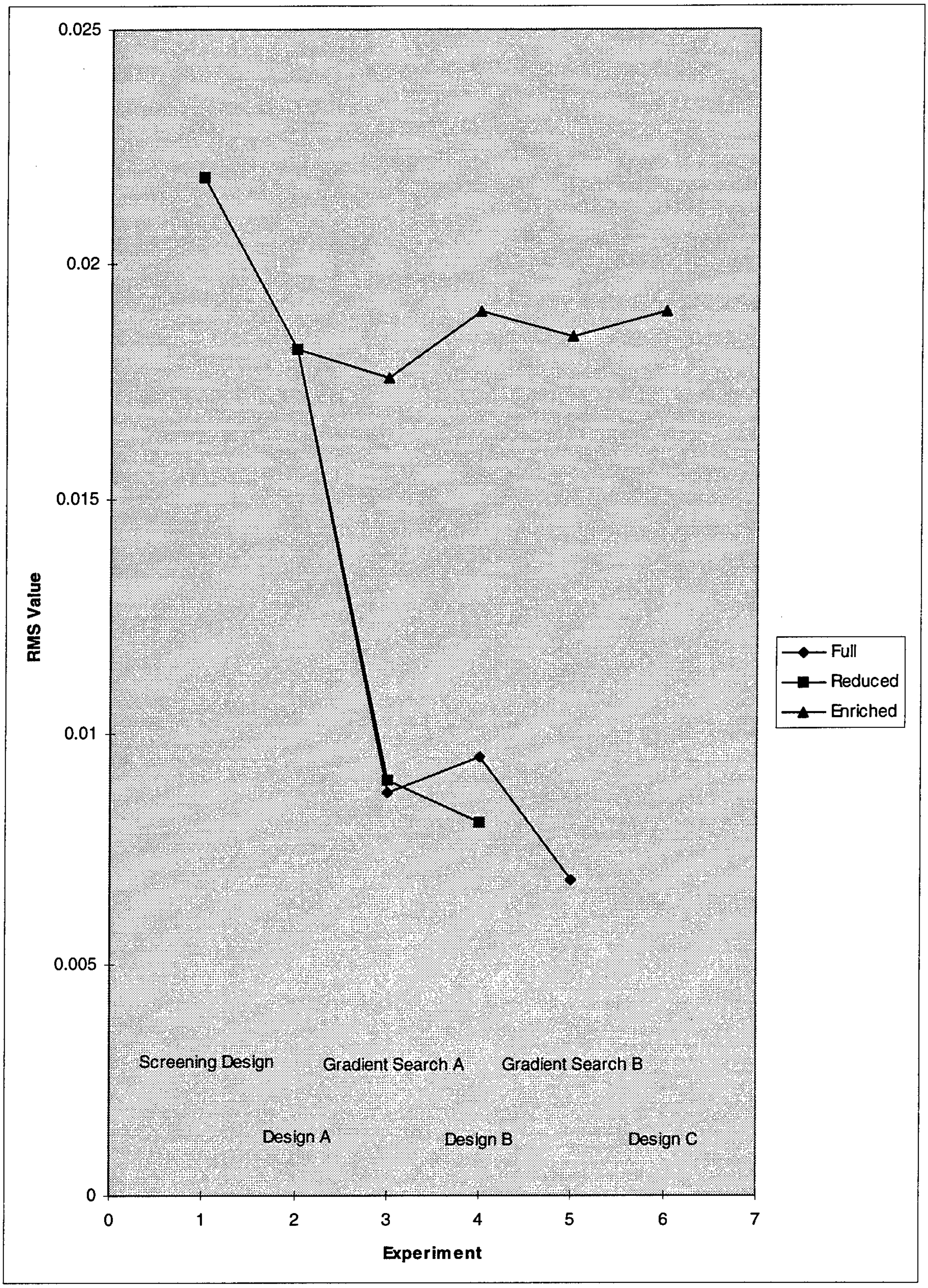

Figure 3.27 Response Values

IV. Conclusions and Recommendations

Response Surface Methodology can be used to calibrate groundwater model flow parameters within a bounded parameter space. Therefore, if a feasible region can be defined for the parameters, RSM can provide nonunique calibrated values which produce accurate hydraulic heads. All three calibration attempts in this study quickly and efficiently converged on calibrated parameter values, although the first two attempts using the full and reduced target data sets provided a better match to the actual target data set.

The use of the screening design in each of the calibrations provided a good starting point for each of the calibration efforts. The low response obtained might even have been "good enough" to halt the calibration process after the 12 experiments conducted for each screening design. However, it was also shown that the use of a screening design could inadvertently eliminate influential parameters from the study.

The use of only the first-order design phase and a "flatter" response (RMS as opposed to SSE) provided final parameter values in all three calibration attempts which produced hydraulic head values which closely matched the actual head values without using a second order design phase.

The reduction of the calibration target data set did not degrade calibration effort. Similar calibrated parameter values were obtained using both the full and reduced target data sets, and the hydraulic heads produced from each calibration matched the actual values very closely. The use of an enriched target data set also provided calibrated heads which matched the actual values. However, the reduced target data set calibration required fewer calculations and provided more accurate head values.

A recommendation for future study would be to devise a response surface methodology which optimizes flow and transport either sequentially or simultaneously. Examining calibration methods using a dual response or a combined response might provide insights as to how this task could be accomplished.

Appendix A

Full Target Data Set Design Settings and Responses

This appendix contains the *Microsoft Excel* worksheets used to record the data from the experiments conducted during the full target data set calibration. Parameter settings and responses are included for designs A and B and the steepest descent searches for each design.

Screening Design											
Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	16	1.0000E-05	1.0000E-02	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-02	1.0000E-03	1.0000E-03	1.0000E-07	1.0000E-04
2	16	1.0000E-01	1.0000E-06	1.0000E-02	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-03	1.0000E-03	1.0000E-04	1.0000E-07
3	6	1.0000E-01	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-06	1.0000E-06	1.0000E-07	1.0000E-03	1.0000E-04	1.0000E-04
4	16	1.0000E-05	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-06	1.0000E-07	1.0000E-07	1.0000E-04	1.0000E-04
5	16	1.0000E-01	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-07	1.0000E-07	1.0000E-07	1.0000E-04
6	16	1.0000E-01	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-03	1.0000E-07	1.0000E-07	1.0000E-07
7	6	1.0000E-01	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-07	1.0000E-03	1.0000E-07	1.0000E-07
8	6	1.0000E-05	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-03	1.0000E-07	1.0000E-04	1.0000E-07
9	6	1.0000E-05	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-03	1.0000E-03	1.0000E-07	1.0000E-04
10	16	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-07	1.0000E-03	1.0000E-04	1.0000E-07
11	6	1.0000E-01	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-03	1.0000E-07	1.0000E-04	1.0000E-04
12	6	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-07	1.0000E-07	1.0000E-07	1.0000E-07

Screening Design Responses				
Run	SSE	RMS	MAE	ME
1	593.94	1.0647	0.56444	0.56066
2	360.43	0.82936	0.45557	0.38962
3	1127.8	1.4671	0.76166	0.21639
4	498.47	0.97533	0.53558	0.41831
5	380.9	0.85259	0.48167	0.47267
6	163	0.55773	0.27235	0.27082
7	1115.2	1.4588	0.70275	0.05397
8	379.52	0.85105	0.47095	0.40469
9	547.84	1.0225	0.54872	0.54455
10	2046.3	1.9761	1.2347	0.42098
11	947.99	1.345	0.70223	0.70055
12	0.25047	0.021863	0.012243	-0.0019567

Design A											
Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	10	1.0000E-05	9.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	9.0000E-06	9.0000E-07	9.0000E-07	1.0000E-07	9.0000E-07
2	10	9.0000E-05	1.0000E-06	9.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	9.0000E-07	9.0000E-07	9.0000E-07	1.0000E-07
3	6	9.0000E-05	9.0000E-06	1.0000E-06	9.0000E-06	1.0000E-06	1.0000E-06	1.0000E-07	9.0000E-07	9.0000E-07	9.0000E-07
4	10	1.0000E-05	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	1.0000E-06	1.0000E-07	1.0000E-07	9.0000E-07	9.0000E-07
5	10	9.0000E-05	1.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	1.0000E-07	1.0000E-07	1.0000E-07	9.0000E-07
6	10	9.0000E-05	9.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-07	1.0000E-07	1.0000E-07	1.0000E-07
7	6	9.0000E-05	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	1.0000E-07	9.0000E-07	1.0000E-07	1.0000E-07
8	6	1.0000E-05	9.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	9.0000E-07	1.0000E-07	9.0000E-07	1.0000E-07
9	6	1.0000E-05	1.0000E-06	9.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-07	9.0000E-07	1.0000E-07	9.0000E-07
10	10	1.0000E-05	1.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	9.0000E-06	1.0000E-07	9.0000E-07	9.0000E-07	1.0000E-07
11	6	9.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	9.0000E-07	1.0000E-07	9.0000E-07	9.0000E-07
12	6	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-07	1.0000E-07	1.0000E-07	1.0000E-07

Design A Responses				
Run	SSE	RMS	MAE	ME
1	0.13483	0.016041	0.0090647	-0.0005043
2	0.19707	0.019393	0.010245	-0.0025291
3	0.93298	0.042196	0.021537	0.0010182
4	0.887	0.041143	0.021204	0.0023496
5	0.5179	0.031438	0.015683	0.0015364
6	0.1734	0.018191	0.0091005	-0.0017923
7	0.32509	0.024908	0.012334	-0.0029585
8	0.24346	0.021555	0.010963	-0.0013884
9	0.2465	0.021689	0.011473	-0.0007553
10	0.6597	0.035482	0.018407	-0.0011708
11	0.17559	0.018306	0.0097137	0.0011693
12	0.25047	0.021863	0.012243	-0.0019567

Design A Steepest Descent Experiments

Steps	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	8	5.1265E-05	4.3996E-06	4.6954E-06	3.9063E-06	4.7262E-06	5.6338E-06	8.0981E-07	4.7270E-07	3.3367E-07	3.8865E-07
2	8	5.2529E-05	3.7992E-06	4.3909E-06	2.8126E-06	4.4525E-06	6.2676E-06	1.1196E-06	4.4540E-07	1.6735E-07	2.7729E-07
3	7	5.3794E-05	3.1988E-06	4.0863E-06	1.7189E-06	4.1787E-06	6.9013E-06	1.4294E-06	4.1810E-07	1.0000E-07	1.6594E-07
4	7	5.5058E-05	2.5984E-06	3.7817E-06	1.0000E-06	3.9050E-06	7.5351E-06	1.7392E-06	3.9080E-07	1.0000E-07	1.0000E-07
5	7	5.6323E-05	1.9980E-06	3.4772E-06	1.0000E-06	3.6312E-06	8.1689E-06	2.0491E-06	3.6350E-07	1.0000E-07	1.0000E-07
6	7	5.7587E-05	1.3976E-06	3.1726E-06	1.0000E-06	3.3574E-06	8.8027E-06	2.3589E-06	3.3620E-07	1.0000E-07	1.0000E-07
7	7	5.8852E-05	1.0000E-06	2.8680E-06	1.0000E-06	3.0837E-06	9.4364E-06	2.6687E-06	3.0890E-07	1.0000E-07	1.0000E-07
8	6	6.0116E-05	1.0000E-06	2.5635E-06	1.0000E-06	2.8099E-06	1.0070E-05	2.9785E-06	2.8160E-07	1.0000E-07	1.0000E-07
9	6	6.1381E-05	1.0000E-06	2.2589E-06	1.0000E-06	2.5362E-06	1.0704E-05	3.2883E-06	2.5430E-07	1.0000E-07	1.0000E-07
10	6	6.2645E-05	1.0000E-06	1.9543E-06	1.0000E-06	2.2624E-06	1.1338E-05	3.5981E-06	2.2700E-07	1.0000E-07	1.0000E-07
11	6	6.3910E-05	1.0000E-06	1.6497E-06	1.0000E-06	1.9886E-06	1.1972E-05	3.9079E-06	1.9970E-07	1.0000E-07	1.0000E-07
12	6	6.5174E-05	1.0000E-06	1.3452E-06	1.0000E-06	1.7149E-06	1.2605E-05	4.2177E-06	1.7240E-07	1.0000E-07	1.0000E-07
13	6	6.6439E-05	1.0000E-06	1.0406E-06	1.0000E-06	1.4411E-06	1.3239E-05	4.5275E-06	1.4510E-07	1.0000E-07	1.0000E-07
14	6	6.7703E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.1674E-06	1.3873E-05	4.8373E-06	1.1780E-07	1.0000E-07	1.0000E-07
15	6	6.8968E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.4507E-05	5.1472E-06	1.0000E-07	1.0000E-07	1.0000E-07
16	6	7.0232E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.5140E-05	5.4570E-06	1.0000E-07	1.0000E-07	1.0000E-07
17	6	7.1497E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.5774E-05	5.7668E-06	1.0000E-07	1.0000E-07	1.0000E-07
18	6	7.2761E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.6408E-05	6.0766E-06	1.0000E-07	1.0000E-07	1.0000E-07
19	6	7.4026E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.7042E-05	6.3864E-06	1.0000E-07	1.0000E-07	1.0000E-07

Design A Steepest Descent Responses

Step	SSE	RMS	MAE	ME
1	0.21905	0.020446	0.011166	-0.0022532
2	0.20125	0.019598	0.010357	-0.0023595
3	0.17143	0.018088	0.0094773	-0.0023711
4	0.12946	0.015718	0.0083712	-0.0023473
5	0.11461	0.014789	0.0079412	-0.0021171
6	0.10022	0.01383	0.0075116	-0.0017827
7	0.087074	0.012891	0.0070597	-0.0013734
8	0.077569	0.012167	0.0067101	-0.0012039
9	0.068935	0.01147	0.0063622	-0.0010178
10	0.061041	0.010793	0.0060035	-0.0008101
11	0.053825	0.010135	0.0056191	-0.000571
12	0.047286	0.0094995	0.0051784	-0.0002854
13	0.041649	0.0089154	0.0046332	7.979E-05
14	0.040763	0.0088199	0.0042825	0.0003558
15	0.040854	0.0088298	0.0040195	0.0005898
16	0.040223	0.0087613	0.0038468	0.0007221
17	0.039858	0.0087215	0.0036875	0.0008533
18	0.039735	0.0087081	0.0035508	0.0009825
19	0.039856	0.0087213	0.0034329	0.0011126

	Design B										
Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	8	3.2761E-05	5.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	2.0408E-05	1.0077E-05	5.0000E-07	1.0000E-07	5.0000E-07
2	8	1.1276E-04	1.0000E-06	5.0000E-06	1.0000E-06	1.0000E-06	1.2408E-05	1.0077E-05	5.0000E-07	5.0000E-07	1.0000E-07
3	6	1.1276E-04	5.0000E-06	1.0000E-06	5.0000E-06	1.0000E-06	1.2408E-05	2.0766E-06	5.0000E-07	5.0000E-07	5.0000E-07
4	8	3.2761E-05	5.0000E-06	5.0000E-06	1.0000E-06	5.0000E-06	1.2408E-05	2.0766E-06	1.0000E-07	5.0000E-07	5.0000E-07
5	8	1.1276E-04	1.0000E-06	5.0000E-06	5.0000E-06	1.0000E-06	2.0408E-05	2.0766E-06	1.0000E-07	1.0000E-07	5.0000E-07
6	8	1.1276E-04	5.0000E-06	1.0000E-06	5.0000E-06	5.0000E-06	1.2408E-05	1.0077E-05	1.0000E-07	1.0000E-07	1.0000E-07
7	6	1.1276E-04	5.0000E-06	5.0000E-06	1.0000E-06	5.0000E-06	2.0408E-05	2.0766E-06	5.0000E-07	1.0000E-07	1.0000E-07
8	6	3.2761E-05	5.0000E-06	5.0000E-06	5.0000E-06	1.0000E-06	2.0408E-05	1.0077E-05	1.0000E-07	5.0000E-07	1.0000E-07
9	6	3.2761E-05	1.0000E-06	5.0000E-06	5.0000E-06	5.0000E-06	1.2408E-05	1.0077E-05	5.0000E-07	1.0000E-07	5.0000E-07
10	8	3.2761E-05	1.0000E-06	1.0000E-06	5.0000E-06	5.0000E-06	2.0408E-05	2.0766E-06	5.0000E-07	5.0000E-07	1.0000E-07
11	6	1.1276E-04	1.0000E-06	1.0000E-06	1.0000E-06	5.0000E-06	2.0408E-05	1.0077E-05	1.0000E-07	5.0000E-07	5.0000E-07
12	6	3.2761E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.2408E-05	2.0766E-06	1.0000E-07	1.0000E-07	1.0000E-07

	Design B Responses			
Run	SSE	RMS	MAE	ME
1	0.047002	0.009471	0.0033446	0.0011077
2	0.067541	0.011353	0.004768	0.0004221
3	0.093027	0.013324	0.007336	-0.0015533
4	0.10098	0.013882	0.0068886	-0.0011103
5	0.09895	0.013742	0.0070267	-0.0006653
6	0.058759	0.010589	0.0052334	-0.0001809
7	0.09351	0.013359	0.0072167	-0.0022981
8	0.091612	0.013222	0.0059743	-0.0002005
9	0.09859	0.013717	0.0068138	0.0002566
10	0.10762	0.014331	0.007268	-0.0005696
11	0.051556	0.0099191	0.0048699	0.00261
12	0.057312	0.010458	0.0056712	-0.0004918

Design B Steepest Descent Experiments											
Steps	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	7	7.8246E-05	2.9679E-06	1.9027E-06	1.9714E-06	2.5852E-06	1.6900E-05	8.5108E-06	2.6327E-07	2.5393E-07	2.9271E-07
2	7	8.3731E-05	2.9358E-06	1.0000E-06	1.0000E-06	2.1704E-06	1.6759E-05	1.0635E-05	2.2655E-07	2.0786E-07	2.8542E-07
3	7	8.9216E-05	2.9038E-06	1.0000E-06	1.0000E-06	1.7557E-06	1.6617E-05	1.2760E-05	1.8982E-07	1.6179E-07	2.7813E-07
4	7	9.4701E-05	2.8717E-06	1.0000E-06	1.0000E-06	1.3409E-06	1.6476E-05	1.4884E-05	1.5309E-07	1.1572E-07	2.7083E-07

Design B Steepest Descent Responses				
Steps	SSE	RMS	MAE	ME
1	0.049083	0.0096783	0.0051401	-0.0003991
2	0.024367	0.0068192	0.0027209	0.0008143
3	0.030109	0.0075802	0.0026023	0.0012932
4	0.040916	0.0088365	0.003206	0.0018295

Appendix B

Reduced Target Data Set Design Settings and Responses

This appendix contains the *Microsoft Excel* worksheets used to record the data from the experiments conducted during the reduced target data set calibration. Parameter settings and responses are included for designs A and B and the steepest descent searches for each design.

Screening Design											
Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	16	1.0000E-05	1.0000E-02	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-02	1.0000E-03	1.0000E-03	1.0000E-07	1.0000E-04
2	16	1.0000E-01	1.0000E-06	1.0000E-02	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-03	1.0000E-03	1.0000E-04	1.0000E-07
3	6	1.0000E-01	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-06	1.0000E-06	1.0000E-07	1.0000E-03	1.0000E-04	1.0000E-04
4	16	1.0000E-05	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-06	1.0000E-07	1.0000E-07	1.0000E-04	1.0000E-04
5	16	1.0000E-01	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-07	1.0000E-07	1.0000E-07	1.0000E-04
6	16	1.0000E-01	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-03	1.0000E-07	1.0000E-07	1.0000E-07
7	6	1.0000E-01	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-07	1.0000E-03	1.0000E-07	1.0000E-07
8	6	1.0000E-05	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-03	1.0000E-07	1.0000E-04	1.0000E-07
9	6	1.0000E-05	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-03	1.0000E-03	1.0000E-07	1.0000E-04
10	16	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-07	1.0000E-03	1.0000E-04	1.0000E-07
11	6	1.0000E-01	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-03	1.0000E-07	1.0000E-04	1.0000E-04
12	6	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-07	1.0000E-07	1.0000E-07	1.0000E-07

Screening Design Responses				
Run	SSE	RMS	MAE	ME
1	67.707	1.6796	1.1078	1.107
2	43.814	1.3511	0.94859	0.72691
3	104.51	2.0868	1.1104	1.1023
4	55.467	1.5202	1.0016	1.0016
5	45.682	1.3796	1.0032	1.0029
6	21.09	0.93742	0.57366	0.57232
7	68.695	1.6918	0.89618	0.88689
8	44.465	1.3611	1.0045	0.78327
9	65.103	1.647	1.1219	1.121
10	199.85	2.8857	2.1644	1.2425
11	100.52	2.0466	1.2691	1.2671
12	0.012936	0.023217	0.01715	0.016015

Design A											
Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	10	1.0000E-05	9.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	9.0000E-06	9.0000E-07	9.0000E-07	1.0000E-07	9.0000E-07
2	10	9.0000E-05	1.0000E-06	9.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	9.0000E-07	9.0000E-07	9.0000E-07	1.0000E-07
3	6	9.0000E-05	9.0000E-06	1.0000E-06	9.0000E-06	1.0000E-06	1.0000E-06	1.0000E-07	9.0000E-07	9.0000E-07	9.0000E-07
4	10	1.0000E-05	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	1.0000E-06	1.0000E-07	1.0000E-07	9.0000E-07	9.0000E-07
5	10	9.0000E-05	1.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	1.0000E-07	1.0000E-07	1.0000E-07	9.0000E-07
6	10	9.0000E-05	9.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-07	1.0000E-07	1.0000E-07	1.0000E-07
7	6	9.0000E-05	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	1.0000E-07	9.0000E-07	1.0000E-07	1.0000E-07
8	6	1.0000E-05	9.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	9.0000E-07	1.0000E-07	9.0000E-07	1.0000E-07
9	6	1.0000E-05	1.0000E-06	9.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-07	9.0000E-07	1.0000E-07	9.0000E-07
10	10	1.0000E-05	1.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	9.0000E-06	1.0000E-07	9.0000E-07	9.0000E-07	1.0000E-07
11	6	9.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	9.0000E-07	1.0000E-07	9.0000E-07	9.0000E-07
12	6	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-07	1.0000E-07	1.0000E-07	1.0000E-07

Design A Responses				
Run	SSE	RMS	MAE	ME
1	0.0059219	0.015708	0.011862	-0.0078214
2	0.0055171	0.015162	0.011702	-0.011634
3	0.037752	0.039661	0.025968	-0.0075684
4	0.04038	0.041018	0.027082	-0.0071131
5	0.034348	0.037831	0.024573	-0.015148
6	0.0090561	0.019425	0.012477	-0.012408
7	0.0086677	0.019004	0.012318	-0.011183
8	0.0076892	0.017899	0.013549	-0.0092684
9	0.0085623	0.018888	0.013791	-0.011653
10	0.01462	0.024682	0.018378	-0.0036125
11	0.0076529	0.017857	0.01289	-0.0056114
12	0.012936	0.023217	0.01715	-0.016015

Design A Steepest Descent Experiments

Steps	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	8	4.7279E-05	4.4550E-06	4.6656E-06	4.0451E-06	5.3110E-06	5.8815E-06	7.9086E-07	5.8726E-07	4.1974E-07	3.1359E-07
2	7	4.4558E-05	3.9101E-06	4.3312E-06	3.0902E-06	5.6220E-06	6.7631E-06	1.0817E-06	6.7452E-07	3.3948E-07	1.2718E-07
3	7	4.1837E-05	3.3651E-06	3.9968E-06	2.1353E-06	5.9329E-06	7.6446E-06	1.3726E-06	7.6177E-07	2.5922E-07	1.0000E-07
4	7	3.9116E-05	2.8201E-06	3.6624E-06	1.1803E-06	6.2439E-06	8.5262E-06	1.6635E-06	8.4903E-07	1.7896E-07	1.0000E-07
5	6	3.6396E-05	2.2751E-06	3.3280E-06	1.0000E-06	6.5549E-06	9.4077E-06	1.9543E-06	9.3629E-07	1.0000E-07	1.0000E-07
6	6	3.3675E-05	1.7302E-06	2.9936E-06	1.0000E-06	6.8659E-06	1.0289E-05	2.2452E-06	1.0235E-06	1.0000E-07	1.0000E-07
7	6	3.0954E-05	1.1852E-06	2.6592E-06	1.0000E-06	7.1769E-06	1.1171E-05	2.5360E-06	1.1108E-06	1.0000E-07	1.0000E-07
8	6	2.8233E-05	1.0000E-06	2.3248E-06	1.0000E-06	7.4878E-06	1.2052E-05	2.8269E-06	1.1981E-06	1.0000E-07	1.0000E-07
9	6	2.5512E-05	1.0000E-06	1.9904E-06	1.0000E-06	7.7988E-06	1.2934E-05	3.1178E-06	1.2853E-06	1.0000E-07	1.0000E-07
10	6	2.2791E-05	1.0000E-06	1.6560E-06	1.0000E-06	8.1098E-06	1.3815E-05	3.4086E-06	1.3726E-06	1.0000E-07	1.0000E-07
11	6	2.0070E-05	1.0000E-06	1.3216E-06	1.0000E-06	8.4208E-06	1.4697E-05	3.6995E-06	1.4598E-06	1.0000E-07	1.0000E-07
12	6	1.7349E-05	1.0000E-06	1.0000E-06	1.0000E-06	8.7318E-06	1.5579E-05	3.9904E-06	1.5471E-06	1.0000E-07	1.0000E-07
13	6	1.4628E-05	1.0000E-06	1.0000E-06	1.0000E-06	9.0427E-06	1.6460E-05	4.2812E-06	1.6344E-06	1.0000E-07	1.0000E-07
14	6	1.1907E-05	1.0000E-06	1.0000E-06	1.0000E-06	9.3537E-06	1.7342E-05	4.5721E-06	1.7216E-06	1.0000E-07	1.0000E-07
15	6	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	9.6647E-06	1.8223E-05	4.8629E-06	1.8089E-06	1.0000E-07	1.0000E-07

Design A Steepest Descent Results

Step	SSE	RMS	MAE	ME
1	0.01111	0.021516	0.015088	-0.014923
2	0.010777	0.021191	0.014657	-0.014589
3	0.010244	0.02066	0.014081	-0.014013
4	0.0085079	0.018828	0.012459	-0.01239
5	0.0072395	0.017368	0.011087	-0.011018
6	0.0059227	0.015709	0.010008	-0.0099398
7	0.0041908	0.013214	0.0083669	-0.0082982
8	0.0030165	0.011211	0.0071335	-0.0069529
9	0.0023673	0.0099317	0.0063426	-0.0060883
10	0.0017208	0.0084676	0.0054245	-0.0050863
11	0.0010767	0.006698	0.0044467	-0.003849
12	0.0004912	0.0045242	0.0032005	-0.0022062
13	0.0003216	0.0036607	0.0026283	-0.001344
14	0.0002267	0.0030733	0.0020663	-0.0003802
15	0.0002298	0.0030944	0.0017446	0.0006002

Design B											
Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	8	3.2761E-05	5.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	2.1042E-05	1.0386E-05	5.0000E-07	1.0000E-07	5.0000E-07
2	8	1.1276E-04	1.0000E-06	5.0000E-06	1.0000E-06	1.0000E-06	1.3042E-05	1.0386E-05	5.0000E-07	5.0000E-07	1.0000E-07
3	6	1.1276E-04	5.0000E-06	1.0000E-06	5.0000E-06	1.0000E-06	1.3042E-05	2.3864E-06	5.0000E-07	5.0000E-07	5.0000E-07
4	8	3.2761E-05	5.0000E-06	5.0000E-06	1.0000E-06	5.0000E-06	1.3042E-05	2.3864E-06	1.0000E-07	5.0000E-07	5.0000E-07
5	8	1.1276E-04	1.0000E-06	5.0000E-06	5.0000E-06	1.0000E-06	2.1042E-05	2.3864E-06	1.0000E-07	1.0000E-07	5.0000E-07
6	8	1.1276E-04	5.0000E-06	1.0000E-06	5.0000E-06	5.0000E-06	1.3042E-05	1.0386E-05	1.0000E-07	1.0000E-07	1.0000E-07
7	6	1.1276E-04	5.0000E-06	5.0000E-06	1.0000E-06	5.0000E-06	2.1042E-05	2.3864E-06	5.0000E-07	1.0000E-07	1.0000E-07
8	6	3.2761E-05	5.0000E-06	5.0000E-06	5.0000E-06	1.0000E-06	2.1042E-05	1.0386E-05	1.0000E-07	5.0000E-07	1.0000E-07
9	6	3.2761E-05	1.0000E-06	5.0000E-06	5.0000E-06	5.0000E-06	1.3042E-05	1.0386E-05	5.0000E-07	1.0000E-07	5.0000E-07
10	8	3.2761E-05	1.0000E-06	1.0000E-06	5.0000E-06	5.0000E-06	2.1042E-05	2.3864E-06	5.0000E-07	5.0000E-07	1.0000E-07
11	6	1.1276E-04	1.0000E-06	1.0000E-06	1.0000E-06	5.0000E-06	2.1042E-05	1.0386E-05	1.0000E-07	5.0000E-07	5.0000E-07
12	6	3.2761E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.3042E-05	2.3864E-06	1.0000E-07	1.0000E-07	1.0000E-07

Design B Responses				
Run	SSE	RMS	MAE	ME
1	0.0001746	0.0026968	0.0018692	0.0015284
2	0.0007897	0.0057364	0.0041135	-0.0026817
3	0.0054181	0.015025	0.0098089	-0.008812
4	0.0067068	0.016717	0.010969	-0.009374
5	0.0074898	0.017666	0.013123	-0.011355
6	0.0021846	0.0095406	0.0059789	-0.0057805
7	0.0025252	0.010257	0.0064481	-0.0063413
8	0.003327	0.011774	0.0077477	-0.0067889
9	0.0007853	0.0057203	0.0042597	-0.0013402
10	0.0015284	0.0079802	0.0067253	-0.0008456
11	0.0027657	0.010735	0.0063171	0.0054423
12	3.52E-03	1.21E-02	8.12E-03	-8.01E-03

Design B Steepest Descent Experiments

Steps	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	7	1.7026E-05	2.7683E-06	2.6262E-06	2.6388E-06	9.6635E-06	1.7627E-05	7.1349E-06	2.6854E-06	2.6188E-07	2.5736E-07
2	7	1.4945E-05	2.5367E-06	2.2524E-06	2.2776E-06	9.9732E-06	1.7913E-05	9.6977E-06	3.6493E-06	2.2376E-07	2.1471E-07
3	7	1.2864E-05	2.3050E-06	1.8787E-06	1.9164E-06	1.0283E-05	1.8198E-05	1.2260E-05	4.6131E-06	1.8565E-07	1.7207E-07

Design B Steepest Descent Responses

Steps	SSE	RMS	MAE	ME
1	0.0029027	0.010998	0.0068817	-0.0066961
2	0.0011452	0.0069077	0.0046755	-0.0037626
3	0.0002497	0.0032254	0.0023689	-0.0002607

Appendix C

Data Enrichment Residuals and Results

This appendix contains the *Microsoft Excel* worksheets which were used to organize the residual values obtained from *Surfer* and to compute the error statistics for each enrichment method. All 524 residual values and the error statistics (SSE, RMS, MAE, ME) are included for each data enrichment technique evaluated during the study.

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
1	0	280.9	300.5226	2.76413	0.32043	5.01785	4.59262	1.83011	0.70767	0.480408
2	0	283.8	300.5207	2.76181	0.31766	5.01541	4.59009	1.82742	0.70538	0.478363
3	0	287	300.521	2.761719	0.31702	5.01514	4.58975	1.8269	0.70532	0.478546
4	0	290.05	300.5225	2.762817	0.31763	5.01611	4.59061	1.82758	0.70645	0.479919
5	0	292.94	300.521	2.760956	0.31528	5.0141	4.58853	1.82532	0.70459	0.478302
6	0	293.86	300.522	2.76178	0.31601	5.01495	4.58933	1.82608	0.70551	0.479279
7	0	294.47	300.5216	2.761353	0.31543	5.01444	4.58881	1.82553	0.70505	0.478851
8	0	295.23	300.5489	2.788452	0.3425	5.0416	4.61594	1.8526	0.73224	0.506104
9	0	296.14	300.5583	2.797791	0.35162	5.05081	4.62515	1.86176	0.74152	0.515472
10	0	297.06	300.5587	2.798096	0.35175	5.05106	4.62537	1.86191	0.74179	0.515808
11	0	297.97	300.559	2.798187	0.35178	5.05121	4.62549	1.86197	0.742	0.516083
12	0	298.89	300.5598	2.798859	0.35233	5.05185	4.6261	1.86255	0.74271	0.516876
13	0	299.8	300.5612	2.80014	0.35345	5.05307	4.62729	1.86368	0.74399	0.518219
14	0	300.56	300.5628	2.801697	0.35483	5.05457	4.62875	1.86511	0.74551	0.519806
15	30.48	280.9	300.4607	2.165558	0.26266	3.96579	3.51535	1.49582	0.54285	0.3927
16	30.48	283.8	300.4574	2.161743	0.25845	3.96179	3.51129	1.49158	0.53918	0.389282
17	30.48	286.85	300.4529	2.156738	0.25299	3.9566	3.50601	1.48612	0.5343	0.384674
18	30.48	289.89	300.4478	2.151093	0.24686	3.95056	3.49991	1.47977	0.52881	0.379425
19	30.48	292.79	300.4442	2.146851	0.24225	3.94605	3.49536	1.47498	0.52481	0.375702
20	30.48	293.7	300.4423	2.144806	0.23999	3.94385	3.49313	1.47269	0.52277	0.373749
21	30.48	294.31	300.4416	2.143951	0.23907	3.94296	3.49222	1.47174	0.52197	0.373016
22	30.48	295.08	300.4267	2.128906	0.22391	3.92783	3.47708	1.45654	0.50699	0.358093
23	30.48	295.99	300.4205	2.122467	0.21741	3.92133	3.47058	1.44995	0.50064	0.351868
24	30.48	296.91	300.4188	2.120605	0.21536	3.91934	3.46857	1.44788	0.49881	0.350098
25	30.48	297.82	300.4172	2.118835	0.21347	3.91745	3.46668	1.44592	0.4971	0.34848
26	30.48	298.73	300.4152	2.116638	0.21115	3.91516	3.46436	1.44354	0.49496	0.346436
27	30.48	299.65	300.4128	2.114014	0.20844	3.91251	3.46167	1.44077	0.49246	0.343994
28	30.48	300.41	300.4104	2.111481	0.20575	3.90985	3.45902	1.43805	0.48996	0.341553
29	60.96	280.75	300.4003	1.516174	0.21036	2.75989	2.36823	1.12747	0.39645	0.315979
30	60.96	283.65	300.3979	1.512939	0.20682	2.7562	2.36453	1.12347	0.39362	0.313416
31	60.96	286.85	300.3964	1.51062	0.20404	2.7533	2.36166	1.12024	0.39163	0.311768
32	60.96	289.89	300.3956	1.509003	0.20206	2.75119	2.35953	1.11777	0.39038	0.310822
33	60.96	292.79	300.3934	1.506012	0.19873	2.74771	2.35608	1.11398	0.38776	0.308472
34	60.96	293.7	300.3933	1.505676	0.19827	2.74722	2.35556	1.1134	0.38751	0.308319
35	60.96	294.31	300.3928	1.505035	0.19751	2.74643	2.3548	1.11255	0.3869	0.30777
36	60.96	295.08	300.4059	1.517914	0.21033	2.75925	2.36758	1.12524	0.3999	0.320862
37	60.96	295.99	300.4102	1.52182	0.21417	2.76294	2.37131	1.12882	0.40402	0.325073
38	60.96	296.91	300.4099	1.52124	0.21347	2.76209	2.37048	1.12784	0.4036	0.324738
39	60.96	297.82	300.4096	1.520569	0.21274	2.7612	2.36963	1.1268	0.40314	0.324371
40	60.96	298.73	300.4095	1.520172	0.21219	2.76047	2.36893	1.12595	0.40286	0.324188
41	60.96	299.65	300.4099	1.520172	0.21219	2.76032	2.36881	1.12564	0.40311	0.324554
42	60.96	300.41	300.4104	1.520416	0.21234	2.76032	2.36884	1.12555	0.40347	0.324982
43	91.44	280.75	300.2791	0.7641602	0.11023	1.36862	1.13995	0.66263	0.21494	0.18808
44	91.44	283.65	300.2762	0.7597351	0.10565	1.36295	1.13452	0.65622	0.2114	0.184815
45	91.44	286.69	300.2732	0.7548828	0.1008	1.35675	1.12866	0.6492	0.20767	0.181366
46	91.44	289.74	300.27	0.7499084	0.09573	1.3504	1.12262	0.64197	0.20377	0.177734
47	91.44	292.64	300.2669	0.7451477	0.09091	1.34433	1.11682	0.6351	0.20001	0.174225
48	91.44	293.55	300.2664	0.7441406	0.08984	1.34287	1.11548	0.63339	0.19928	0.173584

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
49	91.44	294.16	300.2658	0.7431946	0.0889	1.34164	1.11432	0.63199	0.19858	0.172913
50	91.44	294.92	300.2647	0.7416992	0.08734	1.33975	1.11252	0.62991	0.1973	0.171722
51	91.44	295.84	300.2636	0.7400513	0.08569	1.33771	1.11057	0.62759	0.19598	0.170471
52	91.44	296.75	300.2627	0.7385559	0.0842	1.33585	1.1088	0.62549	0.19485	0.169434
53	91.44	297.67	300.2616	0.736969	0.08255	1.3338	1.10684	0.6232	0.19354	0.168213
54	91.44	298.58	300.2605	0.7352905	0.0809	1.33176	1.10489	0.62088	0.19226	0.166992
55	91.44	299.5	300.2592	0.73349	0.07904	1.3295	1.10272	0.61838	0.19073	0.165527
56	91.44	300.26	300.258	0.731842	0.07739	1.32752	1.10083	0.61618	0.18936	0.164246
57	121.92	280.6	300.0844	0.199585	0.08426	0.32358	0.25775	0.23114	0.00043	-0.00418
58	121.92	283.49	300.0829	0.1950073	0.08002	0.31653	0.25143	0.22171	-0.00247	-0.00714
59	121.92	286.54	300.0844	0.1932983	0.07867	0.31223	0.24792	0.2149	-0.00238	-0.00711
60	121.92	289.59	300.0871	0.1927795	0.07849	0.30905	0.24558	0.20923	-0.00113	-0.00595
61	121.92	291.04	300.0865	0.1905212	0.07648	0.30557	0.24249	0.20438	-0.00247	-0.00735
62	121.92	292.49	300.0859	0.1882935	0.07446	0.30209	0.23941	0.19952	-0.00378	-0.00873
63	121.92	293.4	300.0846	0.1860046	0.07227	0.29898	0.23654	0.19553	-0.00558	-0.01053
64	121.92	294.01	300.0841	0.1848145	0.0712	0.29727	0.23499	0.19324	-0.00638	-0.01135
65	121.92	294.77	300.1006	0.2004089	0.08691	0.31223	0.25018	0.20749	0.00974	0.0047
66	121.92	295.69	300.106	0.2048645	0.09143	0.3158	0.254	0.21017	0.01465	0.009613
67	121.92	296.6	300.1059	0.2036743	0.09042	0.3139	0.25235	0.2074	0.0141	0.009033
68	121.92	297.51	300.1055	0.202301	0.08914	0.31168	0.25037	0.20432	0.01324	0.008148
69	121.92	298.43	300.1053	0.2010803	0.08804	0.30966	0.2486	0.20142	0.01257	0.007416
70	121.92	299.34	300.1054	0.2001343	0.08725	0.30795	0.24713	0.19885	0.01221	0.00705
71	121.92	300.11	300.1056	0.1994934	0.0867	0.30661	0.246	0.19678	0.01202	0.006805
72	137.16	292.49	299.8694	0.1723022	0.11807	0.32184	0.21277	0.06384	-0.21375	-0.22659
73	137.16	293.4	299.8755	0.1774292	0.12326	0.32614	0.21732	0.06726	-0.20813	-0.22098
74	137.16	294.01	299.8755	0.1770935	0.12286	0.32547	0.21674	0.06631	-0.20828	-0.22107
75	137.16	294.77	299.9274	0.2284241	0.17429	0.37659	0.26791	0.1171	-0.15659	-0.16928
76	137.16	295.69	299.9456	0.2461548	0.19189	0.3938	0.28522	0.13394	-0.13864	-0.15125
77	137.16	296.6	299.947	0.2468872	0.19272	0.39423	0.28574	0.13397	-0.13748	-0.14996
78	137.16	297.51	299.9477	0.2470703	0.19284	0.39395	0.28558	0.1333	-0.13702	-0.14941
79	137.16	298.43	299.9492	0.2479553	0.19376	0.39447	0.28619	0.13345	-0.13577	-0.14807
80	137.16	299.19	299.9509	0.2492676	0.19498	0.39536	0.28717	0.13403	-0.13428	-0.14645
81	137.16	299.95	299.9532	0.2510681	0.19678	0.39682	0.28873	0.13516	-0.13217	-0.14429
82	152.4	280.6	299.6593	0.3963928	0.2818	0.74838	0.52057	0.09811	-0.39651	-0.43088
83	152.4	283.49	299.657	0.3922729	0.27765	0.74301	0.5155	0.09149	-0.3996	-0.43362
84	152.4	286.54	299.6559	0.3892822	0.2746	0.73865	0.51147	0.08585	-0.40149	-0.43518
85	152.4	289.59	299.6552	0.3867493	0.27194	0.73468	0.50787	0.08063	-0.40302	-0.43634
86	152.4	291.11	299.6538	0.3843689	0.26956	0.73166	0.505	0.07693	-0.40482	-0.43799
87	152.4	292.49	299.6529	0.3826294	0.26776	0.72928	0.50278	0.07397	-0.40613	-0.43912
88	152.4	293.4	299.65	0.3791504	0.26428	0.7254	0.49899	0.06973	-0.40927	-0.44214
89	152.4	294.01	299.6494	0.3781738	0.26331	0.72418	0.49783	0.06824	-0.41	-0.44284
90	152.4	294.77	299.6523	0.3806763	0.26572	0.72626	0.5	0.07001	-0.40732	-0.44003
91	152.4	295.69	299.6529	0.3806763	0.26572	0.72586	0.49969	0.06921	-0.40698	-0.43961
92	152.4	296.6	299.6521	0.3793335	0.26434	0.72409	0.49802	0.06705	-0.40802	-0.44055
93	152.4	297.51	299.6513	0.3779297	0.26297	0.72235	0.49637	0.06494	-0.40906	-0.44147
94	152.4	298.43	299.6502	0.3765259	0.26141	0.72064	0.49472	0.06296	-0.41037	-0.44266
95	152.4	299.04	299.6494	0.3753967	0.26028	0.71945	0.49353	0.06161	-0.41129	-0.44348
96	152.4	299.65	299.6484	0.374176	0.25897	0.71805	0.49216	0.06003	-0.41245	-0.44455

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
97	167.64	292.41	299.3457	0.5236511	0.34344	1.07455	0.74875	0.00668	-0.6738	-0.74152
98	167.64	293.25	299.3462	0.5238037	0.34351	1.07449	0.74872	0.00638	-0.67352	-0.74109
99	167.64	293.86	299.3457	0.5230103	0.34271	1.07361	0.74783	0.00531	-0.67413	-0.74164
100	167.64	294.62	299.3465	0.523468	0.34311	1.07388	0.74817	0.00537	-0.67352	-0.74091
101	167.64	295.53	299.3462	0.5228271	0.34232	1.073	0.74728	0.00421	-0.67404	-0.74127
102	167.64	296.45	299.3455	0.521698	0.34116	1.07169	0.746	0.00266	-0.67496	-0.74207
103	167.64	297.36	299.3447	0.5205994	0.3399	1.07028	0.74466	0.00098	-0.67596	-0.74295
104	167.64	298.28	299.3441	0.5195923	0.33881	1.06909	0.74347	-0.00049	-0.67679	-0.74362
105	167.64	298.89	299.3438	0.5190125	0.33823	1.06842	0.74283	-0.00134	-0.67722	-0.74396
106	167.64	299.34	299.3436	0.5186462	0.33777	1.0679	0.74231	-0.00198	-0.67752	-0.7442
107	182.88	280.6	299.0376	0.6609192	0.42984	1.39768	1.00546	-0.04205	-0.91461	-1.03732
108	182.88	283.34	299.0362	0.6583557	0.42703	1.39447	1.00235	-0.04605	-0.91666	-1.03894
109	182.88	286.39	299.0374	0.6585388	0.42685	1.39432	1.00217	-0.047	-0.91614	-1.03796
110	182.88	289.44	299.0398	0.6599426	0.42786	1.39533	1.00317	-0.04675	-0.91449	-1.0358
111	182.88	290.96	299.0388	0.6584778	0.42615	1.39365	1.0015	-0.0488	-0.91586	-1.03693
112	182.88	292.33	299.0386	0.6578369	0.42535	1.39285	1.0007	-0.04993	-0.91635	-1.0372
113	182.88	293.25	299.0361	0.6550293	0.42242	1.38992	0.9978	-0.05307	-0.91907	-1.0398
114	182.88	293.86	299.0355	0.6542664	0.42154	1.38907	0.99692	-0.05411	-0.91983	-1.04044
115	182.88	294.62	299.0422	0.6607056	0.42792	1.39542	1.0033	-0.04794	-0.9133	-1.03378
116	182.88	295.53	299.0439	0.6620789	0.4292	1.39673	1.00458	-0.04684	-0.9118	-1.03214
117	182.88	296.45	299.043	0.6609802	0.42789	1.39542	1.00327	-0.0484	-0.91293	-1.03311
118	182.88	297.36	299.0419	0.6595764	0.42636	1.39389	1.00177	-0.05014	-0.91425	-1.0343
119	182.88	298.12	299.0407	0.6581116	0.42484	1.39237	1.00024	-0.05185	-0.91562	-1.03555
120	182.88	298.73	299.0396	0.6567993	0.42346	1.39099	0.99887	-0.05338	-0.91684	-1.03668
121	182.88	299.04	299.0388	0.6559143	0.42252	1.39005	0.99789	-0.05441	-0.91776	-1.03754
122	198.12	292.26	298.6278	0.6781616	0.40579	1.57401	1.14102	-0.20248	-1.23868	-1.42734
123	198.12	293.1	298.6339	0.684021	0.41153	1.57983	1.14685	-0.19687	-1.23279	-1.4213
124	198.12	293.7	298.6341	0.6841125	0.41147	1.57983	1.14682	-0.19702	-1.23276	-1.42117
125	198.12	294.47	298.6975	0.7472839	0.47455	1.64301	1.20999	-0.13403	-1.16953	-1.35782
126	198.12	295.38	298.7208	0.7702942	0.49747	1.66599	1.23297	-0.11124	-1.14645	-1.3346
127	198.12	296.3	298.7234	0.7727356	0.49966	1.6683	1.23526	-0.10916	-1.1441	-1.33209
128	198.12	297.21	298.7257	0.7747192	0.50159	1.67032	1.23724	-0.10733	-1.142	-1.32983
129	198.12	297.82	298.7285	0.7774353	0.50412	1.67291	1.23984	-0.10489	-1.13937	-1.32712
130	198.12	298.43	298.7318	0.7804565	0.50717	1.67603	1.24295	-0.1019	-1.1362	-1.32385
131	198.12	298.73	298.734	0.7826233	0.50925	1.67813	1.24506	-0.09988	-1.13409	-1.32169
132	213.36	280.45	298.2366	0.7102051	0.41214	1.7413	1.29111	-0.32196	-1.51148	-1.78372
133	213.36	283.34	298.233	0.7058716	0.40729	1.73679	1.28653	-0.32715	-1.51578	-1.78757
134	213.36	286.39	298.2274	0.6993713	0.40039	1.73019	1.27991	-0.33447	-1.52216	-1.79346
135	213.36	289.44	298.2209	0.6920776	0.39261	1.72272	1.27237	-0.34265	-1.52942	-1.8002
136	213.36	290.96	298.219	0.6897278	0.39005	1.72034	1.26996	-0.34537	-1.53168	-1.80222
137	213.36	292.18	298.217	0.687439	0.38757	1.71799	1.26761	-0.34799	-1.53397	-1.80432
138	213.36	293.1	298.2122	0.6824951	0.38239	1.71295	1.26254	-0.35324	-1.53903	-1.80924
139	213.36	293.7	298.2111	0.6811829	0.38101	1.71173	1.26129	-0.35461	-1.54031	-1.81039
140	213.36	294.47	298.1597	0.6296082	0.32932	1.66016	1.20969	-0.40637	-1.59189	-1.86188
141	213.36	295.38	298.1395	0.6091919	0.30875	1.63974	1.18924	-0.427	-1.61234	-1.88217
142	213.36	296.3	298.1355	0.6049805	0.30438	1.6355	1.18503	-0.43143	-1.61658	-1.88626
143	213.36	296.91	298.1328	0.6020813	0.30142	1.63269	1.18216	-0.43439	-1.61945	-1.88904
144	213.36	297.51	298.1293	0.5984497	0.29767	1.62903	1.1785	-0.4382	-1.62311	-1.89261

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
145	213.36	297.82	298.1269	0.5959778	0.29514	1.62656	1.176	-0.44073	-1.62561	-1.89505
146	213.36	298.12	298.1244	0.5934753	0.29251	1.62396	1.17343	-0.44339	-1.62817	-1.89758
147	228.6	292.18	297.8667	0.7461853	0.43066	1.88327	1.43643	-0.42606	-1.73856	-2.10306
148	228.6	293.1	297.8617	0.7409973	0.42526	1.87805	1.43118	-0.43149	-1.74381	-2.10815
149	228.6	293.7	297.8607	0.7398682	0.42401	1.87689	1.43002	-0.43277	-1.74497	-2.10922
150	228.6	294.47	297.8326	0.7115173	0.39563	1.84863	1.40176	-0.46121	-1.77325	-2.13739
151	228.6	295.38	297.822	0.7007446	0.38464	1.8378	1.3909	-0.47226	-1.78412	-2.1481
152	228.6	296.3	297.8204	0.6988831	0.38266	1.83603	1.3891	-0.47424	-1.78595	-2.14981
153	228.6	296.91	297.8198	0.6981506	0.38181	1.83533	1.38837	-0.4751	-1.78674	-2.15051
154	228.6	297.36	297.8195	0.6978149	0.38132	1.83493	1.38797	-0.47559	-1.7872	-2.15088
155	228.6	297.82	297.8196	0.6977844	0.38126	1.83496	1.388	-0.47568	-1.7872	-2.15082
156	243.84	280.45	297.5328	0.8132019	0.49536	2.02631	1.60169	-0.47626	-1.8895	-2.3602
157	243.84	283.19	297.5296	0.8093872	0.49103	2.02261	1.5979	-0.48059	-1.89349	-2.36377
158	243.84	286.24	297.5249	0.8040161	0.48511	2.01737	1.59256	-0.48654	-1.89911	-2.3689
159	243.84	289.44	297.5196	0.7979126	0.47852	2.01148	1.58658	-0.49319	-1.90537	-2.37466
160	243.84	290.96	297.5179	0.795929	0.4762	2.00952	1.5846	-0.49548	-1.90747	-2.37656
161	243.84	292.18	297.5164	0.7941589	0.47418	2.00778	1.58279	-0.49753	-1.90936	-2.37824
162	243.84	293.1	297.517	0.7945251	0.47443	2.00821	1.58322	-0.49728	-1.90903	-2.37778
163	243.84	293.7	297.5165	0.7938843	0.47369	2.0076	1.58261	-0.49802	-1.9097	-2.37833
164	243.84	294.47	297.5174	0.7946167	0.47427	2.00836	1.58334	-0.49744	-1.90903	-2.37756
165	243.84	295.38	297.5171	0.7940674	0.4736	2.0079	1.58286	-0.49814	-1.90961	-2.37799
166	243.84	296.3	297.5162	0.7929993	0.47235	2.00684	1.58176	-0.49939	-1.91077	-2.379
167	243.84	296.75	297.5157	0.79245	0.47165	2.00623	1.58115	-0.50009	-1.91141	-2.37958
168	243.84	297.21	297.5152	0.7918091	0.47098	2.00568	1.58057	-0.50076	-1.91205	-2.38016
169	243.84	297.51	297.5148	0.7913208	0.47046	2.00522	1.58011	-0.50131	-1.91254	-2.38059
170	259.08	292.1	297.2129	0.8770142	0.56497	2.12915	1.74359	-0.5141	-1.98709	-2.5669
171	259.08	292.94	297.2124	0.8763428	0.56415	2.12854	1.74295	-0.51489	-1.98785	-2.56754
172	259.08	293.55	297.2118	0.8756409	0.56329	2.12787	1.74225	-0.51572	-1.98868	-2.56827
173	259.08	294.31	297.2121	0.8757629	0.56329	2.12805	1.74243	-0.51572	-1.98862	-2.56812
174	259.08	295.23	297.2116	0.875061	0.56244	2.12744	1.74179	-0.51654	-1.98941	-2.56876
175	259.08	296.14	297.2108	0.874115	0.56122	2.1265	1.74081	-0.5177	-1.99054	-2.56976
176	259.08	296.6	297.2104	0.8735962	0.56064	2.12604	1.74033	-0.51828	-1.99109	-2.57025
177	259.08	296.91	297.2102	0.8733215	0.56033	2.12579	1.74011	-0.51859	-1.99136	-2.5705
178	259.08	297.21	297.21	0.8730164	0.56	2.12555	1.73984	-0.51889	-1.9917	-2.57077
179	274.32	280.29	296.9137	0.957428	0.66504	2.21036	1.87589	-0.51443	-2.00858	-2.69739
180	274.32	283.19	296.9117	0.9548035	0.6619	2.20798	1.87344	-0.51749	-2.01151	-2.69989
181	274.32	286.24	296.9112	0.9535828	0.66013	2.20703	1.87241	-0.51917	-2.01306	-2.70102
182	274.32	289.29	296.9112	0.9529114	0.65887	2.20673	1.87201	-0.52023	-2.01419	-2.70181
183	274.32	290.81	296.9101	0.9514465	0.65717	2.20544	1.8707	-0.52188	-2.01584	-2.70331
184	274.32	292.03	296.9093	0.9504089	0.65588	2.20453	1.86975	-0.5231	-2.01709	-2.70441
185	274.32	292.94	296.9066	0.9474792	0.6528	2.20172	1.86691	-0.52615	-2.02014	-2.70734
186	274.32	293.55	296.906	0.9467163	0.65195	2.20108	1.86624	-0.52695	-2.02097	-2.70807
187	274.32	294.31	296.9071	0.9476929	0.65274	2.20209	1.86725	-0.52612	-2.02014	-2.70718
188	274.32	295.23	296.907	0.9473267	0.65228	2.2019	1.86704	-0.52652	-2.02057	-2.70749
189	274.32	295.69	296.9065	0.9467773	0.65158	2.20136	1.86646	-0.52719	-2.02127	-2.70813
190	274.32	296.14	296.906	0.9461975	0.65091	2.20081	1.86591	-0.52786	-2.02191	-2.70874
191	274.32	296.6	296.9056	0.9456482	0.65033	2.20035	1.86545	-0.52841	-2.02249	-2.70926
192	274.32	296.91	296.9052	0.9452209	0.64981	2.19992	1.86502	-0.52893	-2.02301	-2.70972

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
193	289.56	291.95	296.5244	0.9347534	0.66568	2.15637	1.8794	-0.60614	-2.08057	-2.86237
194	289.56	292.79	296.5304	0.9404907	0.6713	2.16229	1.88528	-0.60043	-2.07495	-2.85669
195	289.56	293.4	296.5305	0.9404602	0.67114	2.16235	1.88532	-0.60056	-2.0751	-2.85681
196	289.56	294.16	296.5806	0.990387	0.72095	2.2124	1.93536	-0.55072	-2.0253	-2.80695
197	289.56	295.08	296.5981	1.007721	0.73807	2.22983	1.95276	-0.53351	-2.00818	-2.78976
198	289.56	295.53	296.5988	1.008331	0.73856	2.23047	1.9534	-0.53299	-2.00769	-2.78925
199	289.56	295.99	296.5997	1.009125	0.73929	2.23135	1.95425	-0.53223	-2.00699	-2.78848
200	289.56	296.3	296.6001	1.009369	0.73956	2.23172	1.95462	-0.53195	-2.00671	-2.78818
201	289.56	296.6	296.6004	1.009644	0.73972	2.232	1.9549	-0.53174	-2.00653	-2.78799
202	304.8	280.29	296.1323	0.9075928	0.67316	2.05957	1.8447	-0.68494	-2.09546	-2.94907
203	304.8	283.04	296.1312	0.9058838	0.6709	2.05826	1.84329	-0.68698	-2.09772	-2.95111
204	304.8	286.08	296.1346	0.9085083	0.67307	2.06143	1.84641	-0.68463	-2.09558	-2.94873
205	304.8	289.13	296.1397	0.9129639	0.67688	2.06628	1.8512	-0.68057	-2.09177	-2.94467
206	304.8	290.66	296.1387	0.9116516	0.67526	2.06516	1.85001	-0.6821	-2.09341	-2.94623
207	304.8	291.88	296.1396	0.9122009	0.67563	2.06595	1.85077	-0.68164	-2.09305	-2.94574
208	304.8	292.79	296.1358	0.9082642	0.67145	2.06207	1.84689	-0.68573	-2.0972	-2.94986
209	304.8	293.4	296.1351	0.9073792	0.6705	2.06134	1.84613	-0.68665	-2.09818	-2.95078
210	304.8	294.16	296.1418	0.9139099	0.67691	2.06799	1.85278	-0.68021	-2.0918	-2.94434
211	304.8	294.62	296.1433	0.9152832	0.67819	2.06946	1.85425	-0.67886	-2.09052	-2.94305
212	304.8	295.08	296.1447	0.916626	0.67941	2.07083	1.85559	-0.67761	-2.08933	-2.94186
213	304.8	295.53	296.1442	0.9159241	0.67868	2.07028	1.85504	-0.67828	-2.09006	-2.9426
214	304.8	295.84	296.1437	0.9153748	0.67807	2.06979	1.85452	-0.67889	-2.0907	-2.94324
215	304.8	296.14	296.1432	0.9148254	0.67743	2.06924	1.854	-0.6795	-2.09137	-2.94388
216	320.04	291.88	295.5982	0.7270508	0.52905	1.77643	1.62408	-0.9061	-2.2085	-3.09653
217	320.04	292.79	295.604	0.732666	0.53445	1.78217	1.62982	-0.9006	-2.20313	-3.09113
218	320.04	293.4	295.6041	0.7325745	0.53427	1.78223	1.62985	-0.90073	-2.20334	-3.09134
219	320.04	293.78	295.6351	0.7635498	0.56512	1.8132	1.66083	-0.86984	-2.17252	-3.06049
220	320.04	294.16	295.6662	0.7945251	0.59607	1.8443	1.6919	-0.83887	-2.1416	-3.02957
221	320.04	294.62	295.6764	0.8045959	0.60605	1.85446	1.70206	-0.82883	-2.13162	-3.01959
222	320.04	295.08	295.6836	0.811676	0.61307	1.86163	1.70923	-0.82178	-2.12463	-3.0126
223	320.04	295.38	295.6848	0.8128052	0.61417	1.86282	1.71042	-0.82068	-2.12357	-3.01154
224	320.04	295.69	295.686	0.8139648	0.6152	1.86401	1.71158	-0.81958	-2.12253	-3.01047
225	335.28	280.29	295.0844	0.5670776	0.41525	1.4693	1.37744	-1.09042	-2.22986	-3.09842
226	335.28	283.04	295.0802	0.5622253	0.40982	1.46497	1.37305	-1.09558	-2.23557	-3.10431
227	335.28	286.08	295.0716	0.5527954	0.39987	1.45624	1.36429	-1.10526	-2.24588	-3.11478
228	335.28	289.13	295.0623	0.5426636	0.38922	1.44681	1.3548	-1.11563	-2.25687	-3.12595
229	335.28	290.66	295.061	0.5409851	0.38727	1.44547	1.35342	-1.11743	-2.25897	-3.12814
230	335.28	291.88	295.0568	0.5364685	0.38251	1.44119	1.34915	-1.12207	-2.26386	-3.13312
231	335.28	292.79	295.048	0.5274353	0.37332	1.43237	1.3403	-1.1312	-2.27316	-3.14246
232	335.28	293.4	295.0465	0.5258179	0.37155	1.43085	1.33878	-1.1329	-2.27499	-3.14432
233	335.28	293.78	294.9932	0.4723511	0.31808	1.37753	1.28543	-1.18634	-2.32849	-3.19788
234	335.28	294.16	294.9456	0.4247437	0.27029	1.3299	1.23779	-1.23407	-2.37631	-3.24573
235	335.28	294.62	294.9302	0.4092102	0.2547	1.31451	1.22238	-1.24963	-2.39197	-3.26138
236	335.28	294.77	294.9271	0.4060364	0.25153	1.3114	1.21927	-1.25278	-2.39514	-3.26459
237	335.28	294.92	294.924	0.4028931	0.24838	1.30829	1.21619	-1.25592	-2.39832	-3.26776
238	350.52	291.8	294.6143	0.4402161	0.33502	1.15274	1.11285	-1.229	-2.15042	-2.91696
239	350.52	292.64	294.6139	0.4395142	0.33423	1.15234	1.11243	-1.22971	-2.15134	-2.91803
240	350.52	293.25	294.6133	0.4388123	0.33337	1.15173	1.11182	-1.2305	-2.15231	-2.9191

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
241	350.52	293.7	294.6304	0.4556885	0.35025	1.16882	1.12891	-1.21356	-2.1355	-2.90237
242	350.52	294.01	294.6313	0.4565735	0.35101	1.16971	1.12976	-1.2128	-2.13483	-2.90173
243	350.52	294.31	294.6253	0.4504395	0.34488	1.1637	1.12378	-1.21887	-2.14099	-2.90793
244	350.52	294.62	294.6192	0.4442749	0.33862	1.15759	1.11768	-1.2251	-2.14728	-2.91428
245	365.76	280.14	294.1705	0.3432617	0.29169	0.82053	0.82227	-1.32425	-1.97522	-2.55737
246	365.76	282.88	294.1693	0.3412476	0.28925	0.81924	0.82095	-1.32642	-1.97815	-2.56076
247	365.76	285.93	294.1713	0.3424072	0.28983	0.82117	0.82285	-1.32553	-1.97809	-2.56119
248	365.76	287.46	294.1707	0.3413696	0.28851	0.82053	0.82217	-1.32669	-1.97965	-2.56302
249	365.76	288.98	294.1701	0.340332	0.2872	0.81992	0.82153	-1.32785	-1.98126	-2.565
250	365.76	290.5	294.1661	0.3358154	0.28247	0.81589	0.8175	-1.33243	-1.98636	-2.57053
251	365.76	291.72	294.1719	0.3412781	0.28769	0.82166	0.8233	-1.32709	-1.98145	-2.56595
252	365.76	292.64	294.1841	0.3531189	0.29944	0.83386	0.83548	-1.31525	-1.96988	-2.55466
253	365.76	293.25	294.1852	0.3540955	0.30026	0.83496	0.83658	-1.31436	-1.96921	-2.55417
254	365.76	293.7	294.201	0.369751	0.31583	0.85074	0.85233	-1.29877	-1.95377	-2.53885
255	365.76	294.01	294.2577	0.4263306	0.37238	0.90744	0.90903	-1.24219	-1.89728	-2.48245
256	365.76	294.31	294.3144	0.4829102	0.42892	0.96411	0.96573	-1.18561	-1.84082	-2.42606
257	381	290.43	293.6776	0.1889038	0.18906	0.39594	0.42535	-1.46765	-1.81162	-2.13556
258	381	291.57	293.6616	0.1725769	0.17249	0.37991	0.4093	-1.4841	-1.82843	-2.15274
259	381	292.03	293.6492	0.1600342	0.15988	0.36749	0.39691	-1.49667	-1.84116	-2.16559
260	381	292.49	293.6368	0.1474915	0.14725	0.3551	0.38452	-1.50925	-1.85391	-2.1785
261	381	293.1	293.6332	0.1436462	0.14334	0.3515	0.38092	-1.51309	-1.858	-2.18283
262	381	293.48	293.7452	0.2555237	0.25516	0.4635	0.49292	-1.40128	-1.74634	-2.07129
263	381	293.55	293.5524	0.0626831	0.06232	0.27069	0.30011	-1.59412	-1.93921	-2.26419
264	396.24	280.14	293.1873	0.0426941	0.09894	-0.0593	-0.0143	-1.59131	-1.58377	-1.57434
265	396.24	282.73	293.1829	0.0372925	0.09323	-0.0637	-0.0187	-1.59677	-1.59027	-1.58188
266	396.24	285.78	293.1724	0.0257568	0.08121	-0.0742	-0.0292	-1.60852	-1.60324	-1.59607
267	396.24	287.3	293.1672	0.0200501	0.07523	-0.0794	-0.0344	-1.61435	-1.60968	-1.60309
268	396.24	288.83	293.1789	0.0312195	0.08615	-0.0677	-0.0227	-1.60327	-1.59921	-1.59326
269	396.24	290.35	293.1891	0.0408325	0.09558	-0.0575	-0.0126	-1.59372	-1.59027	-1.5849
270	396.24	290.96	293.1994	0.0509338	0.10556	-0.0472	-0.0023	-1.58365	-1.58044	-1.57535
271	396.24	291.57	293.2097	0.0610352	0.11554	-0.0369	0.00803	-1.57361	-1.57068	-1.5658
272	396.24	292.03	293.2262	0.0773926	0.13184	-0.0204	0.02454	-1.55728	-1.55454	-1.54984
273	396.24	292.49	293.2398	0.0908814	0.1452	-0.0068	0.03815	-1.54385	-1.54129	-1.53677
274	396.24	292.87	293.2437	0.0946045	0.14893	-0.0029	0.04205	-1.54013	-1.53769	-1.53333
275	396.24	293.25	293.2476	0.0983582	0.15259	0.00101	0.04593	-1.53641	-1.53412	-1.52991
276	411.48	288.83	292.7306	-0.076813	0.03287	-0.4945	-0.4399	-1.6795	-1.29739	-0.90964
277	411.48	290.35	292.7023	-0.105713	0.00375	-0.5229	-0.4684	-1.7085	-1.32709	-0.94003
278	411.48	290.96	292.6889	-0.119293	-0.01	-0.5364	-0.4818	-1.72217	-1.34103	-0.95428
279	411.48	291.57	292.6752	-0.13324	-0.024	-0.5501	-0.4956	-1.73615	-1.35532	-0.96884
280	411.48	292.03	292.6551	-0.153534	-0.0444	-0.5703	-0.5158	-1.75647	-1.37582	-0.98959
281	411.48	292.33	292.6466	-0.162201	-0.053	-0.5788	-0.5243	-1.76508	-1.38461	-0.9985
282	411.48	292.64	292.638	-0.170868	-0.0618	-0.5874	-0.533	-1.7738	-1.39349	-1.00754
283	426.72	279.99	292.3266	-0.135346	0.02899	-0.8248	-0.7397	-1.69455	-0.9075	-0.11761
284	426.72	282.73	292.3281	-0.134979	0.02899	-0.8235	-0.7386	-1.69431	-0.90854	-0.12
285	426.72	284.26	292.3339	-0.129822	0.03391	-0.8181	-0.7333	-1.68927	-0.9043	-0.11649
286	426.72	285.78	292.3398	-0.124664	0.03897	-0.8125	-0.7278	-1.68411	-0.89993	-0.11285
287	426.72	287.3	292.346	-0.119049	0.04428	-0.8066	-0.722	-1.67868	-0.89529	-0.10895
288	426.72	288.83	292.2823	-0.183472	-0.0203	-0.8706	-0.7862	-1.74316	-0.96057	-0.17499

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
289	426.72	289.59	292.2903	-0.175842	-0.0127	-0.8628	-0.7784	-1.73554	-0.95331	-0.16809
290	426.72	290.35	292.2983	-0.168182	-0.0052	-0.8549	-0.7706	-1.72791	-0.94608	-0.16125
291	426.72	290.96	292.3055	-0.161255	0.00171	-0.8478	-0.7636	-1.72101	-0.93951	-0.15497
292	426.72	291.57	292.3129	-0.154114	0.00873	-0.8406	-0.7564	-1.71393	-0.93274	-0.1485
293	426.72	291.95	292.323	-0.144135	0.01862	-0.8306	-0.7464	-1.70404	-0.92303	-0.13898
294	426.72	292.33	292.3332	-0.134155	0.02859	-0.8205	-0.7363	-1.69403	-0.91321	-0.12936
295	441.96	287.23	291.5764	-0.544647	-0.33	-1.4584	-1.3304	-2.05228	-0.86664	0.277252
296	441.96	288.68	291.7245	-0.397278	-0.1828	-1.3108	-1.183	-1.905	-0.72015	0.423126
297	441.96	289.44	291.7224	-0.399719	-0.1854	-1.3131	-1.1854	-1.9075	-0.72305	0.419891
298	441.96	290.2	291.7218	-0.400726	-0.1865	-1.314	-1.1864	-1.90854	-0.72452	0.418091
299	441.96	290.81	291.7221	-0.400757	-0.1865	-1.3139	-1.1864	-1.90857	-0.72491	0.417481
300	441.96	291.27	291.7228	-0.400238	-0.1861	-1.3134	-1.1859	-1.90814	-0.7247	0.417481
301	441.96	291.72	291.7236	-0.399689	-0.1856	-1.3127	-1.1853	-1.90759	-0.72443	0.417572
302	457.2	279.99	290.8022	-0.968048	-0.7047	-2.0697	-1.8881	-2.4155	-0.83643	0.596954
303	457.2	282.73	290.8014	-0.970337	-0.7072	-2.0715	-1.8902	-2.41785	-0.84027	0.59195
304	457.2	284.1	290.8015	-0.970856	-0.7079	-2.0718	-1.8907	-2.41849	-0.84167	0.589966
305	457.2	285.63	290.8041	-0.969086	-0.7062	-2.0698	-1.8888	-2.41675	-0.84079	0.59021
306	457.2	287.15	290.8067	-0.967285	-0.7046	-2.0677	-1.887	-2.41504	-0.83987	0.590485
307	457.2	287.91	290.8057	-0.968658	-0.7061	-2.069	-1.8883	-2.41647	-0.84174	0.588287
308	457.2	288.68	290.8047	-0.970032	-0.7075	-2.0703	-1.8897	-2.41791	-0.8436	0.586121
309	457.2	289.44	290.8066	-0.968506	-0.7061	-2.0686	-1.8881	-2.41641	-0.84253	0.586853
310	457.2	290.05	290.808	-0.967499	-0.705	-2.0674	-1.887	-2.41534	-0.8418	0.587341
311	457.2	290.43	290.8086	-0.967102	-0.7047	-2.067	-1.8866	-2.41498	-0.84164	0.587341
312	457.2	290.81	290.8092	-0.966675	-0.7043	-2.0666	-1.8863	-2.41461	-0.84149	0.587372
313	472.44	285.63	289.894	-1.528229	-1.2212	-2.7767	-2.5364	-2.90851	-0.96878	0.656372
314	472.44	287.15	289.886	-1.537079	-1.2303	-2.7855	-2.5455	-2.91751	-0.97864	0.646118
315	472.44	287.91	289.8885	-1.535034	-1.2283	-2.7834	-2.5435	-2.9155	-0.97705	0.647492
316	472.44	288.52	289.8909	-1.533051	-1.2263	-2.7813	-2.5415	-2.91348	-0.97537	0.649017
317	472.44	289.29	289.8929	-1.531464	-1.2248	-2.7797	-2.54	-2.91196	-0.97427	0.649902
318	472.44	289.59	289.8939	-1.530701	-1.224	-2.7789	-2.5392	-2.91116	-0.97366	0.650421
319	472.44	289.89	289.8948	-1.529938	-1.2233	-2.7781	-2.5385	-2.91046	-0.97311	0.650879
320	487.68	279.99	289.0108	-2.051758	-1.7053	-3.4099	-3.106	-3.35727	-1.08966	0.625763
321	487.68	282.73	289.0026	-2.061859	-1.7155	-3.4201	-3.1166	-3.36755	-1.10135	0.613892
322	487.68	284.1	288.9962	-2.069183	-1.7229	-3.4276	-3.1243	-3.375	-1.1095	0.605652
323	487.68	285.63	288.9838	-2.082642	-1.7364	-3.441	-3.138	-3.38852	-1.12384	0.591217
324	487.68	286.39	288.9848	-2.082184	-1.7359	-3.4406	-3.1377	-3.38809	-1.12381	0.591217
325	487.68	287.15	288.9858	-2.081757	-1.7355	-3.4401	-3.1374	-3.38767	-1.12375	0.591217
326	487.68	287.91	288.985	-2.083069	-1.7368	-3.4415	-3.1389	-3.38904	-1.12555	0.589356
327	487.68	288.37	288.9835	-2.0849	-1.7387	-3.4433	-3.1408	-3.3909	-1.12763	0.58725
328	487.68	288.68	288.9819	-2.086639	-1.7405	-3.4451	-3.1427	-3.3927	-1.12961	0.585266
329	487.68	288.98	288.9804	-2.088379	-1.7422	-3.4469	-3.1444	-3.39444	-1.1315	0.583344
330	502.92	284.03	288.5374	-2.165344	-1.7863	-3.5923	-3.2263	-3.3894	-0.8577	0.832001
331	502.92	285.63	288.5303	-2.173798	-1.7947	-3.601	-3.2353	-3.39795	-0.86694	0.823029
332	502.92	286.39	288.5253	-2.179443	-1.8004	-3.6068	-3.2412	-3.40363	-0.87296	0.817139
333	502.92	287.15	288.5239	-2.181488	-1.8024	-3.6089	-3.2435	-3.4057	-0.87537	0.81485
334	502.92	287.91	288.5231	-2.182892	-1.8038	-3.6104	-3.2452	-3.40717	-0.87717	0.813202
335	502.92	288.22	288.5231	-2.183075	-1.804	-3.6107	-3.2455	-3.40744	-0.87756	0.812836
336	502.92	288.52	288.5232	-2.183258	-1.8042	-3.6109	-3.2458	-3.40762	-0.87787	0.812592

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
337	518.16	279.84	288.0908	-2.237091	-1.8342	-3.6896	-3.2654	-3.37213	-0.65256	0.911682
338	518.16	282.58	288.0878	-2.242371	-1.8394	-3.6953	-3.2716	-3.37756	-0.65918	0.905518
339	518.16	283.95	288.0786	-2.252655	-1.8496	-3.7058	-3.2824	-3.38794	-0.67017	0.894745
340	518.16	285.48	288.0657	-2.267029	-1.8639	-3.7205	-3.2973	-3.40237	-0.68512	0.880249
341	518.16	286.24	288.0662	-2.267273	-1.8641	-3.721	-3.298	-3.40268	-0.68567	0.880035
342	518.16	287	288.0667	-2.267517	-1.8642	-3.7214	-3.2986	-3.40299	-0.68619	0.879822
343	518.16	287.76	288.0664	-2.268555	-1.8652	-3.7227	-3.3	-3.40408	-0.68753	0.878784
344	518.16	288.07	288.066	-2.269257	-1.8659	-3.7235	-3.3008	-3.40482	-0.68832	0.878113
345	533.4	283.95	287.7528	-2.199249	-1.7803	-3.6446	-3.172	-3.2403	-0.41284	0.97113
346	533.4	285.48	287.7654	-2.188232	-1.7691	-3.6339	-3.1616	-3.22931	-0.40231	0.982269
347	533.4	286.24	287.7641	-2.190216	-1.7711	-3.6362	-3.164	-3.23142	-0.40466	0.980225
348	533.4	287	287.7626	-2.192444	-1.7733	-3.6387	-3.1666	-3.23373	-0.40717	0.978027
349	533.4	287.46	287.7617	-2.193756	-1.7746	-3.6402	-3.1682	-3.23514	-0.40872	0.976654
350	533.4	287.76	287.7612	-2.194611	-1.7754	-3.6411	-3.1692	-3.23593	-0.40961	0.975891
351	548.64	279.84	287.3995	-2.15921	-1.7344	-3.5614	-3.0503	-3.10065	-0.24457	0.920258
352	548.64	282.58	287.3988	-2.163239	-1.7379	-3.5667	-3.0561	-3.10489	-0.24899	0.917481
353	548.64	283.95	287.427	-2.136658	-1.7111	-3.5409	-3.0304	-3.07846	-0.22266	0.944641
354	548.64	284.71	287.4401	-2.124481	-1.6988	-3.5291	-3.0187	-3.06638	-0.2106	0.957153
355	548.64	285.48	287.4532	-2.112305	-1.6865	-3.5172	-3.007	-3.05426	-0.19852	0.969696
356	548.64	286.24	287.4533	-2.113068	-1.6872	-3.5184	-3.0082	-3.05512	-0.19943	0.969238
357	548.64	286.85	287.4545	-2.11261	-1.6866	-3.5182	-3.0082	-3.05472	-0.19907	0.969971
358	548.64	287.15	287.4555	-2.11203	-1.6859	-3.5177	-3.0077	-3.05411	-0.19849	0.970734
359	548.64	287.46	287.4564	-2.111481	-1.6853	-3.5174	-3.0074	-3.05362	-0.19803	0.971375
360	563.88	282.5	286.9598	-2.203308	-1.7817	-3.5331	-2.9988	-3.04105	-0.24142	0.692261
361	563.88	283.95	286.8991	-2.266174	-1.8441	-3.597	-3.0628	-3.1041	-0.30408	0.630707
362	563.88	284.71	286.8676	-2.298859	-1.8765	-3.6301	-3.0961	-3.13681	-0.33658	0.598785
363	563.88	285.48	286.8513	-2.316193	-1.8938	-3.6481	-3.1141	-3.15439	-0.35394	0.582031
364	563.88	286.08	286.8501	-2.318359	-1.8957	-3.6507	-3.1167	-3.15656	-0.35596	0.580475
365	563.88	286.47	286.8484	-2.320587	-1.8978	-3.6532	-3.1193	-3.15888	-0.35815	0.578552
366	563.88	286.85	286.8468	-2.322784	-1.8999	-3.6557	-3.1218	-3.16107	-0.36026	0.576752
367	579.12	279.68	286.5259	-2.221954	-1.8167	-3.4439	-2.9034	-2.9512	-0.2955	0.405029
368	579.12	282.43	286.5208	-2.232361	-1.8257	-3.4571	-2.9166	-2.96201	-0.30417	0.398804
369	579.12	283.8	286.5361	-2.219727	-1.8123	-3.4459	-2.9053	-2.94959	-0.29068	0.413513
370	579.12	284.56	286.54	-2.217224	-1.8094	-3.4442	-2.9036	-2.94727	-0.28775	0.417114
371	579.12	285.32	286.543	-2.215729	-1.8076	-3.4435	-2.9028	-2.94586	-0.28577	0.4198
372	579.12	285.93	286.5424	-2.217438	-1.809	-3.4459	-2.9052	-2.94772	-0.28717	0.418945
373	579.12	286.54	286.542	-2.219055	-1.8103	-3.4481	-2.9074	-2.9494	-0.28836	0.418274
374	594.36	282.43	286.3764	-1.949127	-1.5741	-3.0298	-2.5108	-2.56598	-0.15897	0.338623
375	594.36	283.8	286.3872	-1.94162	-1.5656	-3.0241	-2.505	-2.55878	-0.14987	0.34903
376	594.36	284.56	286.3888	-1.941986	-1.5654	-3.0256	-2.5063	-2.5593	-0.14923	0.350403
377	594.36	285.32	286.3909	-1.941833	-1.5646	-3.0266	-2.5071	-2.55933	-0.14807	0.352325
378	594.36	285.93	286.3904	-1.943909	-1.5662	-3.0296	-2.5099	-2.56149	-0.14932	0.351654
379	594.36	286.39	286.3896	-1.945892	-1.5678	-3.0323	-2.5125	-2.5636	-0.15073	0.350708
380	609.6	279.68	286.2407	-1.637756	-1.31	-2.5428	-2.0718	-2.1384	-0.0657	0.256287
381	609.6	282.43	286.2321	-1.653412	-1.3234	-2.5625	-2.0909	-2.15463	-0.07773	0.246979
382	609.6	283.8	286.2364	-1.652588	-1.3215	-2.5638	-2.0918	-2.15418	-0.07513	0.250916
383	609.6	284.56	286.2372	-1.653687	-1.3221	-2.566	-2.0939	-2.15546	-0.07526	0.251556
384	609.6	285.32	286.237	-1.655823	-1.3236	-2.5693	-2.097	-2.15781	-0.07642	0.251129

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
385	609.6	285.78	286.2364	-1.657623	-1.325	-2.5718	-2.0994	-2.1597	-0.07758	0.250397
386	609.6	286.24	286.2372	-1.65799	-1.325	-2.5728	-2.1003	-2.16016	-0.07733	0.251099
387	624.84	282.43	286.2641	-1.167053	-0.8967	-1.8789	-1.4828	-1.55124	0.12173	0.309052
388	624.84	283.8	286.2536	-1.182587	-0.9104	-1.8975	-1.5005	-1.56717	0.10965	0.298401
389	624.84	284.56	286.248	-1.190887	-0.9178	-1.9076	-1.5101	-1.57584	0.10318	0.292694
390	624.84	285.17	286.2442	-1.19696	-0.923	-1.9149	-1.5171	-1.58203	0.09869	0.288849
391	624.84	285.78	286.2438	-1.199585	-0.9248	-1.9189	-1.5207	-1.58484	0.09756	0.288391
392	624.84	286.24	286.2372	-1.207794	-0.9324	-1.9282	-1.5297	-1.59326	0.09045	0.281738
393	640.08	279.68	286.2814	-0.666718	-0.476	-1.1489	-0.8619	-0.93338	0.25592	0.340332
394	640.08	281.06	286.2888	-0.667114	-0.4733	-1.1544	-0.8654	-0.93457	0.26193	0.347839
395	640.08	282.43	286.2962	-0.667511	-0.4706	-1.1598	-0.8688	-0.9357	0.26794	0.355377
396	640.08	283.8	286.2566	-0.714935	-0.5149	-1.2122	-0.9193	-0.98389	0.22696	0.315857
397	640.08	284.56	286.2351	-0.740814	-0.539	-1.2408	-0.9468	-1.01013	0.20471	0.294434
398	640.08	285.17	286.2162	-0.763123	-0.56	-1.2654	-0.9706	-1.03287	0.18515	0.275574
399	640.08	285.78	286.2145	-0.768311	-0.5637	-1.2728	-0.9771	-1.03836	0.18286	0.273956
400	640.08	286.24	286.2372	-0.74823	-0.5426	-1.2544	-0.958	-1.01852	0.20511	0.296692
401	655.32	282.35	286.1471	-0.35614	-0.2354	-0.6241	-0.4615	-0.51807	0.18005	0.203705
402	655.32	283.8	286.2415	-0.277588	-0.1499	-0.5557	-0.3881	-0.4408	0.27347	0.298828
403	655.32	284.41	286.2886	-0.237061	-0.1065	-0.5195	-0.3498	-0.40088	0.32019	0.346283
404	655.32	285.02	286.3338	-0.198547	-0.065	-0.4853	-0.3134	-0.36288	0.36496	0.391785
405	655.32	285.63	286.3359	-0.203033	-0.0666	-0.4941	-0.3202	-0.36798	0.36667	0.394226
406	655.32	286.24	286.2372	-0.308411	-0.1691	-0.6038	-0.4277	-0.47388	0.26758	0.295837
407	670.56	279.53	286.0327	-0.054688	0.01382	-0.1288	-0.106	-0.15259	0.04123	0.025909
408	670.56	280.9	286.0318	-0.070526	0.00452	-0.1543	-0.1268	-0.16971	0.0394	0.025726
409	670.56	282.27	285.998	-0.132141	-0.0441	-0.2343	-0.1966	-0.23431	0.00833	-0.0025
410	670.56	282.96	285.9482	-0.196259	-0.1015	-0.3079	-0.2649	-0.29996	-0.03995	-0.04932
411	670.56	283.65	285.8983	-0.260437	-0.1591	-0.3816	-0.3333	-0.36572	-0.08838	-0.09628
412	670.56	284.41	285.8386	-0.335968	-0.2272	-0.4677	-0.4135	-0.44305	-0.14639	-0.15271
413	670.56	285.02	285.7869	-0.400452	-0.2857	-0.5405	-0.4817	-0.50885	-0.19678	-0.20178
414	670.56	285.78	285.7808	-0.422363	-0.3003	-0.5731	-0.5083	-0.53256	-0.2012	-0.20462
415	670.56	286.08	286.084	-0.125549	-0.0004	-0.2804	-0.2133	-0.23639	0.10269	0.099915
416	679.7	283.65	285.7319	-0.569397	-0.291	-0.8593	-0.7398	-0.7536	-0.24115	-0.23135
417	679.7	284.41	285.7505	-0.566681	-0.2808	-0.8672	-0.7418	-0.75262	-0.22089	-0.2095
418	679.7	285.02	285.7681	-0.561829	-0.27	-0.8707	-0.7406	-0.74912	-0.20197	-0.18927
419	679.7	285.78	285.7807	-0.565125	-0.2659	-0.8845	-0.7485	-0.75415	-0.18768	-0.17337
420	679.7	285.93	285.9317	-0.417297	-0.1165	-0.7388	-0.6017	-0.60666	-0.03635	-0.02173
421	685.8	280.9	285.461	-0.918335	-0.5264	-1.3129	-1.1515	-1.16409	-0.50916	-0.48901
422	688.85	282.27	285.4391	-1.026886	-0.5563	-1.5054	-1.3058	-1.30798	-0.52597	-0.49576
423	688.85	283.04	285.5026	-0.970703	-0.4969	-1.4538	-1.252	-1.25186	-0.46295	-0.43192
424	688.85	283.65	285.5656	-0.913483	-0.4372	-1.4003	-1.1967	-1.19473	-0.4003	-0.36865
425	688.85	284.41	285.6403	-0.846039	-0.3666	-1.3375	-1.1318	-1.12744	-0.32608	-0.29367
426	688.85	285.02	285.694	-0.798065	-0.3162	-1.2934	-1.0858	-1.07962	-0.27277	-0.23972
427	688.85	285.32	285.6608	-0.834168	-0.351	-1.3313	-1.1229	-1.11578	-0.30615	-0.2728
428	688.85	285.63	285.6276	-0.870239	-0.3859	-1.3693	-1.16	-1.15192	-0.33954	-0.30588
429	694.94	283.04	285.1435	-1.442841	-0.8412	-2.0521	-1.8068	-1.77704	-0.84134	-0.79285
430	694.94	283.65	285.133	-1.459106	-0.855	-2.0721	-1.825	-1.79343	-0.8522	-0.8031
431	694.94	284.41	285.1191	-1.480164	-0.873	-2.0979	-1.8486	-1.8147	-0.86655	-0.81668
432	694.94	284.79	285.1448	-1.45816	-0.8493	-2.0782	-1.8278	-1.79269	-0.8411	-0.79083

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
433	694.94	285.17	285.1704	-1.436127	-0.8258	-2.0586	-1.807	-1.77075	-0.81573	-0.76508
434	701.04	279.53	284.89	-1.80661	-1.0771	-2.5405	-2.2542	-2.19333	-1.11609	-1.04904
435	701.04	280.9	284.8902	-1.819458	-1.0843	-2.5618	-2.2715	-2.20642	-1.11673	-1.04831
436	701.04	282.27	284.8239	-1.898834	-1.158	-2.6495	-2.3552	-2.28598	-1.18387	-1.11401
437	701.04	283.04	284.7843	-1.945587	-1.2017	-2.701	-2.4045	-2.33295	-1.22394	-1.15332
438	701.04	283.65	284.7605	-1.97522	-1.2288	-2.7343	-2.436	-2.36267	-1.24814	-1.17688
439	701.04	284.41	284.7324	-2.010529	-1.261	-2.7744	-2.4738	-2.39813	-1.2767	-1.20468
440	701.04	284.71	284.7132	-2.032623	-1.2818	-2.7983	-2.4969	-2.42029	-1.29608	-1.22376
441	716.28	279.53	284.1201	-2.922913	-1.8482	-4.0079	-3.6128	-3.42419	-1.95718	-1.82559
442	716.28	280.9	284.1134	-2.936737	-1.8592	-4.0262	-3.6294	-3.43787	-1.96494	-1.83215
443	716.28	282.27	284.1147	-2.942596	-1.8622	-4.0367	-3.6381	-3.44357	-1.96469	-1.83075
444	716.28	283.04	284.1121	-2.949097	-1.8672	-4.0457	-3.6462	-3.45004	-1.96787	-1.83328
445	716.28	283.65	284.1061	-2.958282	-1.8751	-4.0569	-3.6567	-3.45914	-1.9743	-1.8392
446	716.28	283.88	284.1049	-2.960724	-1.877	-4.0601	-3.6595	-3.46152	-1.97568	-1.84042
447	716.28	284.1	284.1036	-2.963165	-1.8791	-4.0633	-3.6625	-3.46396	-1.97714	-1.84168
448	731.52	279.38	284.1061	-3.266144	-1.8626	-4.6795	-4.2066	-3.8519	-2.06278	-1.85193
449	731.52	280.75	284.106	-3.270844	-1.8657	-4.6871	-4.2134	-3.85638	-2.06393	-1.85208
450	731.52	282.12	284.1037	-3.277832	-1.871	-4.6969	-4.2225	-3.86307	-2.06726	-1.85443
451	731.52	282.88	284.1032	-3.280945	-1.8732	-4.7015	-4.2267	-3.86597	-2.06833	-1.85495
452	731.52	283.49	284.1038	-3.282349	-1.8739	-4.7043	-4.2292	-3.86734	-2.06821	-1.85437
453	731.52	284.1	284.1036	-3.284637	-1.8754	-4.7078	-4.2324	-3.86948	-2.06888	-1.85458
454	746.76	279.38	284.1089	-3.576538	-1.8605	-5.2934	-4.7719	-4.2207	-2.16858	-1.86755
455	746.76	280.75	284.1071	-3.581604	-1.8646	-5.3004	-4.7787	-4.22553	-2.17136	-1.86948
456	746.76	282.12	284.106	-3.585999	-1.868	-5.3068	-4.7848	-4.22965	-2.17346	-1.8707
457	746.76	282.88	284.1052	-3.588623	-1.8701	-5.3105	-4.7884	-4.23212	-2.17481	-1.87155
458	746.76	283.49	284.1043	-3.591064	-1.8719	-5.3137	-4.7914	-4.23434	-2.17612	-1.8725
459	746.76	284.1	284.1036	-3.593201	-1.8737	-5.3167	-4.7944	-4.23642	-2.17728	-1.87326
460	762	279.38	284.1083	-3.869781	-1.8615	-5.8561	-5.3181	-4.54773	-2.2934	-1.89465
461	762	280.75	284.107	-3.87439	-1.8651	-5.8626	-5.3244	-4.55206	-2.29572	-1.89609
462	762	282.12	284.1055	-3.879211	-1.8689	-5.8694	-5.3309	-4.55658	-2.29822	-1.89771
463	762	282.88	284.1048	-3.881805	-1.8709	-5.873	-5.3344	-4.55896	-2.29947	-1.89847
464	762	283.49	284.1042	-3.883698	-1.8724	-5.8757	-5.337	-4.56076	-2.30051	-1.89914
465	762	284.1	284.1036	-3.885406	-1.8738	-5.878	-5.3393	-4.56235	-2.30148	-1.89981
466	777.24	279.38	284.1084	-4.147461	-1.8616	-6.3752	-5.8416	-4.84457	-2.42639	-1.92752
467	777.24	280.75	284.107	-4.151367	-1.8649	-6.3804	-5.8469	-4.84821	-2.42874	-1.92911
468	777.24	282.12	284.1057	-4.155243	-1.868	-6.3855	-5.852	-4.85172	-2.43097	-1.93057
469	777.24	282.88	284.1049	-4.15744	-1.8699	-6.3885	-5.855	-4.85379	-2.43231	-1.93149
470	777.24	283.49	284.1042	-4.15918	-1.8714	-6.3909	-5.8574	-4.85547	-2.43341	-1.93228
471	777.24	284.1	284.1036	-4.160919	-1.8728	-6.3932	-5.8597	-4.85703	-2.43442	-1.93292
472	792.48	279.38	284.1084	-4.411133	-1.8618	-6.8516	-6.3404	-5.1156	-2.56632	-1.96689
473	792.48	280.75	284.107	-4.414459	-1.8648	-6.8559	-6.3448	-5.11871	-2.56857	-1.96851
474	792.48	282.12	284.1056	-4.417847	-1.8678	-6.8602	-6.3493	-5.12183	-2.57086	-1.97012
475	792.48	282.88	284.1048	-4.419708	-1.8694	-6.8625	-6.3517	-5.12357	-2.57214	-1.97104
476	792.48	283.49	284.1042	-4.421173	-1.8708	-6.8644	-6.3537	-5.12494	-2.57315	-1.97174
477	792.48	284.1	284.1036	-4.422668	-1.872	-6.8663	-6.3556	-5.12628	-2.5741	-1.97241
478	807.72	279.38	284.1085	-4.661133	-1.8619	-7.2851	-6.8111	-5.36356	-2.71115	-2.0123
479	807.72	280.75	284.1071	-4.664124	-1.8647	-7.2887	-6.8149	-5.3663	-2.71338	-2.01395
480	807.72	282.12	284.1057	-4.667114	-1.8674	-7.2922	-6.8187	-5.36905	-2.71555	-2.01556

				Residuals						
				Kriging				Inverse Distance to a Power		
Node	X	Y	Head Value	Exponential	Linear	Quadratic	Spherical	1st Power	Squared	Cubed
481	807.72	282.88	284.1049	-4.668762	-1.869	-7.2943	-6.8208	-5.37061	-2.71683	-2.01654
482	807.72	283.49	284.1042	-4.670105	-1.8703	-7.2959	-6.8226	-5.37192	-2.7179	-2.01733
483	807.72	284.1	284.1036	-4.671448	-1.8715	-7.2975	-6.8243	-5.37311	-2.71884	-2.01804
484	822.96	279.23	284.1082	-4.898529	-1.8623	-7.6758	-7.2509	-5.5914	-2.85977	-2.06403
485	822.96	280.75	284.1067	-4.901489	-1.8651	-7.6792	-7.2545	-5.59412	-2.86209	-2.0658
486	822.96	282.12	284.1053	-4.904144	-1.8677	-7.6823	-7.2578	-5.59662	-2.86426	-2.06747
487	822.96	282.88	284.1046	-4.905548	-1.869	-7.6839	-7.2596	-5.5979	-2.86536	-2.0683
488	822.96	283.49	284.1041	-4.906677	-1.8701	-7.6852	-7.2609	-5.59891	-2.86621	-2.06891
489	822.96	284.1	284.1036	-4.907715	-1.8711	-7.6864	-7.2623	-5.59988	-2.86704	-2.06952
490	838.2	279.23	284.1109	-5.118774	-1.8597	-8.0134	-7.6468	-5.79562	-3.00766	-2.11926
491	838.2	280.75	284.1092	-5.121918	-1.8628	-8.0169	-7.6506	-5.79855	-3.01019	-2.12125
492	838.2	282.12	284.1073	-5.125	-1.8658	-8.0203	-7.6543	-5.80145	-3.01282	-2.12341
493	838.2	282.88	284.1061	-5.126862	-1.8676	-8.0222	-7.6563	-5.80316	-3.0144	-2.12476
494	838.2	283.49	284.1049	-5.128479	-1.8693	-8.024	-7.6582	-5.80478	-3.01593	-2.1261
495	838.2	284.1	284.1036	-5.13028	-1.871	-8.0258	-7.6602	-5.80649	-3.01752	-2.1275
496	853.44	279.23	284.0947	-5.345398	-1.8761	-8.322	-8.0179	-6.00186	-3.17493	-2.19898
497	853.44	280.75	284.0942	-5.347015	-1.8777	-8.3239	-8.0201	-6.00336	-3.17621	-2.19977
498	853.44	281.44	284.0952	-5.346649	-1.8773	-8.3235	-8.0198	-6.00281	-3.17554	-2.19888
499	853.44	282.12	284.10	-5.3463	-1.8769	-8.3232	-8.0197	-6.0024	-3.1750	-2.1981
500	853.44	282.88	284.10	-5.3448	-1.8755	-8.3219	-8.0185	-6.0009	-3.1734	-2.1963
501	853.44	283.49	284.10	-5.3429	-1.8736	-8.3201	-8.0168	-5.9989	-3.1713	-2.1940
502	853.44	284.1	284.10	-5.3403	-1.8709	-8.3175	-8.0144	-5.9962	-3.1685	-2.1910
503	868.68	279.23	283.76	-5.8752	-2.2065	-8.9017	-8.6603	-6.5087	-3.6559	-2.5973
504	868.68	280.75	283.77	-5.8729	-2.2042	-8.8994	-8.6582	-6.5062	-3.6532	-2.5942
505	868.68	281.51	283.77	-5.8686	-2.1999	-8.8951	-8.6540	-6.5018	-3.6487	-2.5896
506	868.68	282.12	283.78	-5.8632	-2.1945	-8.8896	-8.6487	-6.4963	-3.6432	-2.5839
507	868.68	282.88	283.79	-5.8554	-2.1867	-8.8819	-8.6411	-6.4884	-3.6353	-2.5757
508	868.68	283.34	283.79	-5.8497	-2.1811	-8.8762	-8.6355	-6.4827	-3.6295	-2.5699
509	868.68	283.8	283.80	-5.8439	-2.1753	-8.8704	-8.6298	-6.4769	-3.6236	-2.5638
510	883.92	279.07	282.90	-6.9247	-3.0666	-9.9682	-9.7865	-7.5331	-4.6654	-3.5295
511	883.92	280.75	282.90	-6.9295	-3.0716	-9.9729	-9.7915	-7.5378	-4.6700	-3.5338
512	883.92	281.51	282.90	-6.9337	-3.0757	-9.9770	-9.7957	-7.5419	-4.6741	-3.5377
513	883.92	282.12	282.89	-6.9381	-3.0802	-9.9814	-9.8001	-7.5462	-4.6784	-3.5419
514	883.92	282.5	282.89	-6.9424	-3.0846	-9.9857	-9.8045	-7.5505	-4.6827	-3.5461
515	883.92	282.88	282.88	-6.9467	-3.0889	-9.9900	-9.8088	-7.5548	-4.6870	-3.5502
516	899.16	279.07	282.28	-7.7237	-3.6861	-10.7512	-10.6232	-8.3058	-5.4327	-4.2248
517	899.16	280.75	282.28	-7.7284	-3.6909	-10.7555	-10.6278	-8.3103	-5.4372	-4.2290
518	899.16	281.51	282.28	-7.7320	-3.6946	-10.7591	-10.6314	-8.3139	-5.4408	-4.2325
519	899.16	281.89	282.28	-7.7337	-3.6963	-10.7607	-10.6331	-8.3156	-5.4424	-4.2340
520	899.16	282.27	282.27	-7.7354	-3.6980	-10.7623	-10.6347	-8.3172	-5.4441	-4.2356
521	914.40	279.07	281.97	-8.2052	-3.9977	-11.1812	-11.0972	-8.7601	-5.8899	-4.6157
522	914.40	280.75	281.97	-8.2081	-4.0008	-11.1838	-11.1000	-8.7629	-5.8927	-4.6183
523	914.40	281.51	281.97	-8.2087	-4.0014	-11.1841	-11.1003	-8.7634	-5.8932	-4.6186
524	914.40	281.97	281.97	-8.2098	-4.0027	-11.1852	-11.1015	-8.7646	-5.8944	-4.6197
			SSE	2931.69	722.02	7159.52	6202.34	3967.82	1596.75	1593.27
			RMS	2.3653	1.1738	3.6964	3.4404	2.7518	1.7456	1.7437
			MAE	1.6382	0.8470	2.7877	2.4960	1.9597	1.3412	1.3660
			ME	-0.7724	-0.4739	-0.9763	-0.9620	-1.6687	-1.2262	-1.0477

Appendix D

Enriched Target Data Set Design Settings and Responses

This appendix contains the *Microsoft Excel* worksheets used to record the data from the experiments conducted during the Enriched target data set calibration. Parameter settings and responses are included for designs A, B, and C, and the steepest descent searches for each design.

Screening Design

Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	16	1.0000E-05	1.0000E-02	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-02	1.0000E-03	1.0000E-03	1.0000E-07	1.0000E-04
2	16	1.0000E-01	1.0000E-06	1.0000E-02	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-03	1.0000E-03	1.0000E-04	1.0000E-07
3	6	1.0000E-01	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-06	1.0000E-06	1.0000E-07	1.0000E-03	1.0000E-04	1.0000E-04
4	16	1.0000E-05	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-06	1.0000E-07	1.0000E-07	1.0000E-04	1.0000E-04
5	16	1.0000E-01	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-07	1.0000E-07	1.0000E-07	1.0000E-04
6	16	1.0000E-01	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-03	1.0000E-07	1.0000E-07	1.0000E-07
7	6	1.0000E-01	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-07	1.0000E-03	1.0000E-07	1.0000E-07
8	6	1.0000E-05	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-02	1.0000E-03	1.0000E-07	1.0000E-04	1.0000E-07
9	6	1.0000E-05	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-06	1.0000E-03	1.0000E-03	1.0000E-07	1.0000E-04
10	16	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-02	1.0000E-07	1.0000E-03	1.0000E-04	1.0000E-07
11	6	1.0000E-01	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-02	1.0000E-02	1.0000E-03	1.0000E-07	1.0000E-04	1.0000E-04
12	6	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-07	1.0000E-07	1.0000E-07	1.0000E-07

Screening Design Responses

Run	SSE	RMS	MAE	ME
1	1507.4	1.6961	1.4095	0.086809
2	1259.9	1.5506	1.2972	-0.084233
3	2435.6	2.1559	1.593	-0.25747
4	1457.7	1.6679	1.3478	-0.055544
5	1205.2	1.5166	1.2459	-0.0011774
6	975.96	1.3647	1.1171	-0.20303
7	2334.1	2.1105	1.5161	-0.41988
8	1262.4	1.5522	1.2979	-0.069161
9	1452.9	1.6652	1.3927	0.070703
10	3608.4	2.6242	2.0696	-0.052865
11	1900.1	1.9042	1.534	0.22669
12	722.94	1.1746	0.84629	-0.47581

Design A											
Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	10	1.0000E-05	9.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	9.0000E-06	9.0000E-07	9.0000E-07	1.0000E-07	9.0000E-07
2	10	9.0000E-05	1.0000E-06	9.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	9.0000E-07	9.0000E-07	9.0000E-07	1.0000E-07
3	6	9.0000E-05	9.0000E-06	1.0000E-06	9.0000E-06	1.0000E-06	1.0000E-06	1.0000E-07	9.0000E-07	9.0000E-07	9.0000E-07
4	10	1.0000E-05	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	1.0000E-06	1.0000E-07	1.0000E-07	9.0000E-07	9.0000E-07
5	10	9.0000E-05	1.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	1.0000E-07	1.0000E-07	1.0000E-07	9.0000E-07
6	10	9.0000E-05	9.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-07	1.0000E-07	1.0000E-07	1.0000E-07
7	6	9.0000E-05	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	1.0000E-07	9.0000E-07	1.0000E-07	1.0000E-07
8	6	1.0000E-05	9.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-06	9.0000E-07	1.0000E-07	9.0000E-07	1.0000E-07
9	6	1.0000E-05	1.0000E-06	9.0000E-06	9.0000E-06	9.0000E-06	1.0000E-06	9.0000E-07	9.0000E-07	1.0000E-07	9.0000E-07
10	10	1.0000E-05	1.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	9.0000E-06	1.0000E-07	9.0000E-07	9.0000E-07	1.0000E-07
11	6	9.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	9.0000E-06	9.0000E-06	9.0000E-07	1.0000E-07	9.0000E-07	9.0000E-07
12	6	1.0000E-05	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.0000E-07	1.0000E-07	1.0000E-07	1.0000E-07

Design A Responses				
Run	SSE	RMS	MAE	ME
1	722.28	1.1741	0.84649	-0.47511
2	724.39	1.1758	0.84775	-0.47638
3	730.24	1.1805	0.85054	-0.47283
4	728.25	1.1789	0.84941	-0.4715
5	722.16	1.174	0.84475	-0.47232
6	721.87	1.1737	0.84604	-0.47564
7	725.83	1.1769	0.84828	-0.47681
8	724.61	1.1759	0.84851	-0.47524
9	722.47	1.1742	0.84668	-0.47461
10	733.09	1.1828	0.855	-0.47502
11	723.93	1.1754	0.8488	-0.47268
12	722.94	1.1746	0.84629	-0.47581

Design A Steepest Descent Experiments

Steps	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	8	5.5048E-05	4.6154E-06	5.6490E-06	4.3510E-06	4.1587E-06	4.8317E-06	7.2355E-07	3.5818E-07	2.3799E-07	5.3125E-07
2	8	6.0096E-05	4.2308E-06	6.2981E-06	3.7019E-06	3.3173E-06	4.6635E-06	9.4711E-07	2.1635E-07	1.0000E-07	5.6250E-07
3	8	6.5144E-05	3.8462E-06	6.9471E-06	3.0529E-06	2.4760E-06	4.4952E-06	1.1707E-06	1.0000E-07	1.0000E-07	5.9375E-07
4	8	7.0192E-05	3.4616E-06	7.5961E-06	2.4039E-06	1.6347E-06	4.3269E-06	1.3942E-06	1.0000E-07	1.0000E-07	6.2500E-07
5	7	7.5240E-05	3.0770E-06	8.2451E-06	1.7549E-06	1.0000E-06	4.1587E-06	1.6178E-06	1.0000E-07	1.0000E-07	6.5625E-07
6	7	8.0288E-05	2.6924E-06	8.8942E-06	1.1058E-06	1.0000E-06	3.9904E-06	1.8413E-06	1.0000E-07	1.0000E-07	6.8750E-07
7	7	8.5336E-05	2.3077E-06	9.5432E-06	1.0000E-06	1.0000E-06	3.8221E-06	2.0649E-06	1.0000E-07	1.0000E-07	7.1875E-07
8	7	9.0384E-05	1.9231E-06	1.0192E-05	1.0000E-06	1.0000E-06	3.6539E-06	2.2884E-06	1.0000E-07	1.0000E-07	7.5000E-07
9	7	9.5432E-05	1.5385E-06	1.0841E-05	1.0000E-06	1.0000E-06	3.4856E-06	2.5120E-06	1.0000E-07	1.0000E-07	7.8124E-07
10	7	1.0048E-04	1.1539E-06	1.1490E-05	1.0000E-06	1.0000E-06	3.3173E-06	2.7355E-06	1.0000E-07	1.0000E-07	8.1249E-07
11	7	1.0553E-04	1.0000E-06	1.2139E-05	1.0000E-06	1.0000E-06	3.1491E-06	2.9591E-06	1.0000E-07	1.0000E-07	8.4374E-07

Design A Steepest Descent Responses

Steps	SSE	RMS	MAE	ME
1	722.08	1.1739	0.84575	-0.476
2	721.68	1.1736	0.84542	-0.47608
3	721.55	1.1735	0.84534	-0.47589
4	721.5	1.1734	0.8453	-0.47592
5	721.47	1.1734	0.84528	-0.47592
6	721.46	1.1734	0.8453	-0.47589
7	721.47	1.1734	0.84535	-0.47582
8	721.47	1.1734	0.84535	-0.47582
9	721.55	1.1735	0.84558	-0.47557
10	721.65	1.1735	0.84581	-0.47534
11	721.71	1.1736	0.84597	-0.47517

Design B											
Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	10	4.5336E-05	3.6154E-06	5.5432E-06	1.0000E-06	1.0000E-06	6.6442E-06	2.4649E-06	5.0000E-07	1.0000E-07	1.1187E-06
2	10	1.2534E-04	1.0000E-06	1.3543E-05	1.0000E-06	1.0000E-06	1.0000E-06	2.4649E-06	5.0000E-07	5.0000E-07	3.1875E-07
3	6	1.2534E-04	3.6154E-06	5.5432E-06	5.0000E-06	1.0000E-06	1.0000E-06	1.6649E-06	5.0000E-07	5.0000E-07	1.1187E-06
4	10	4.5336E-05	3.6154E-06	1.3543E-05	1.0000E-06	5.0000E-06	1.0000E-06	1.6649E-06	1.0000E-07	5.0000E-07	1.1187E-06
5	10	1.2534E-04	1.0000E-06	1.3543E-05	5.0000E-06	1.0000E-06	6.6442E-06	1.6649E-06	1.0000E-07	1.0000E-07	1.1187E-06
6	10	1.2534E-04	3.6154E-06	5.5432E-06	5.0000E-06	5.0000E-06	1.0000E-06	2.4649E-06	1.0000E-07	1.0000E-07	3.1875E-07
7	6	1.2534E-04	3.6154E-06	1.3543E-05	1.0000E-06	5.0000E-06	6.6442E-06	1.6649E-06	5.0000E-07	1.0000E-07	3.1875E-07
8	6	4.5336E-05	3.6154E-06	1.3543E-05	5.0000E-06	1.0000E-06	6.6442E-06	2.4649E-06	1.0000E-07	5.0000E-07	3.1875E-07
9	6	4.5336E-05	1.0000E-06	1.3543E-05	5.0000E-06	5.0000E-06	1.0000E-06	2.4649E-06	5.0000E-07	1.0000E-07	1.1187E-06
10	10	4.5336E-05	1.0000E-06	5.5432E-06	5.0000E-06	5.0000E-06	6.6442E-06	1.6649E-06	5.0000E-07	5.0000E-07	3.1875E-07
11	6	1.2534E-04	1.0000E-06	5.5432E-06	1.0000E-06	5.0000E-06	6.6442E-06	2.4649E-06	1.0000E-07	5.0000E-07	1.1187E-06
12	6	4.5336E-05	1.0000E-06	5.5432E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.6649E-06	1.0000E-07	1.0000E-07	3.1875E-07

Design B Responses				
Run	SSE	RMS	MAE	ME
1	721.66	1.1735	0.84565	-0.47589
2	722.37	1.1741	0.84694	-0.47529
3	721.96	1.1738	0.84562	-0.47596
4	722.04	1.1739	0.84605	-0.47502
5	721.88	1.1737	0.84592	-0.47496
6	721.44	1.1734	0.84555	-0.47572
7	721.65	1.1735	0.84529	-0.47665
8	722.18	1.174	0.84641	-0.47518
9	722.04	1.1739	0.84642	-0.4751
10	722.78	1.1745	0.84725	-0.47507
11	722.35	1.1741	0.84697	-0.47415
12	721.61	1.1735	0.84575	-0.4757

Design B Steepest Descent Experiments											
Steps	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	8	9.2833E-05	2.9029E-06	9.2219E-06	2.6252E-06	2.6252E-06	3.2932E-06	2.0542E-06	2.6252E-07	1.4471E-07	7.2946E-07
2	8	1.0033E-04	3.4981E-06	8.9006E-06	2.2503E-06	2.2503E-06	2.7643E-06	2.0435E-06	2.2503E-07	1.0000E-07	7.4017E-07
3	8	1.0783E-04	4.0933E-06	8.5793E-06	1.8755E-06	1.8755E-06	2.2354E-06	2.0328E-06	1.8755E-07	1.0000E-07	7.5088E-07
4	7	1.1532E-04	4.6885E-06	8.2580E-06	1.5007E-06	1.5007E-06	1.7065E-06	2.0221E-06	1.5007E-07	1.0000E-07	7.6159E-07
5	7	1.2282E-04	5.2837E-06	7.9368E-06	1.1258E-06	1.1258E-06	1.1775E-06	2.0114E-06	1.1258E-07	1.0000E-07	7.7230E-07
6	7	1.3032E-04	5.8790E-06	7.6155E-06	1.0000E-06	1.0000E-06	1.0000E-06	2.0006E-06	1.0000E-07	1.0000E-07	7.8301E-07
7	7	1.3781E-04	6.4742E-06	7.2942E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.9899E-06	1.0000E-07	1.0000E-07	7.9372E-07
8	7	1.4531E-04	7.0694E-06	6.9729E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.9792E-06	1.0000E-07	1.0000E-07	8.0443E-07
9	7	1.5281E-04	7.6646E-06	6.6516E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.9685E-06	1.0000E-07	1.0000E-07	8.1514E-07
10	6	1.6030E-04	8.2598E-06	6.3303E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.9578E-06	1.0000E-07	1.0000E-07	8.2585E-07
11	6	1.6780E-04	8.8550E-06	6.0090E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.9471E-06	1.0000E-07	1.0000E-07	8.3656E-07
12	6	1.7530E-04	9.4502E-06	5.6877E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.9364E-06	1.0000E-07	1.0000E-07	8.4727E-07
13	6	1.8279E-04	1.0045E-05	5.3665E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.9257E-06	1.0000E-07	1.0000E-07	8.5797E-07

Design B Steepest Descent Responses				
Steps	SSE	RMS	MAE	ME
1	721.6	1.1735	0.84547	-0.47603
2	721.5	1.1734	0.84529	-0.47615
3	721.44	1.1734	0.84519	-0.47619
4	721.39	1.1733	0.84513	-0.47619
5	721.36	1.1733	0.84511	-0.47615
6	721.35	1.1733	0.84512	-0.47611
7	721.35	1.1733	0.84511	-0.47611
8	721.34	1.1733	0.8451	-0.47611
9	721.34	1.1733	0.8451	-0.47611
10	721.34	1.1733	0.8451	-0.4761
11	721.34	1.1733	0.84511	-0.47609
12	721.35	1.1733	0.84511	-0.47608
13	721.35	1.1733	0.84512	-0.47606

Design C											
Run	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	8	1.0531E-04	9.8790E-06	3.6155E-06	1.0000E-06	1.0000E-06	5.0000E-06	2.3792E-06	5.0000E-07	1.0000E-07	1.2044E-06
2	8	1.8531E-04	1.8790E-06	1.1616E-05	1.0000E-06	1.0000E-06	1.0000E-06	2.3792E-06	5.0000E-07	5.0000E-07	4.0443E-07
3	6	1.8531E-04	9.8790E-06	3.6155E-06	5.0000E-06	1.0000E-06	1.0000E-06	1.5792E-06	5.0000E-07	5.0000E-07	1.2044E-06
4	8	1.0531E-04	9.8790E-06	1.1616E-05	1.0000E-06	5.0000E-06	1.0000E-06	1.5792E-06	1.0000E-07	5.0000E-07	1.2044E-06
5	8	1.8531E-04	1.8790E-06	1.1616E-05	5.0000E-06	1.0000E-06	5.0000E-06	1.5792E-06	1.0000E-07	1.0000E-07	1.2044E-06
6	8	1.8531E-04	9.8790E-06	3.6155E-06	5.0000E-06	5.0000E-06	1.0000E-06	2.3792E-06	1.0000E-07	1.0000E-07	4.0443E-07
7	6	1.8531E-04	9.8790E-06	1.1616E-05	1.0000E-06	5.0000E-06	5.0000E-06	1.5792E-06	5.0000E-07	1.0000E-07	4.0443E-07
8	6	1.0531E-04	9.8790E-06	1.1616E-05	5.0000E-06	1.0000E-06	5.0000E-06	2.3792E-06	1.0000E-07	5.0000E-07	4.0443E-07
9	6	1.0531E-04	1.8790E-06	1.1616E-05	5.0000E-06	5.0000E-06	1.0000E-06	2.3792E-06	5.0000E-07	1.0000E-07	1.2044E-06
10	8	1.0531E-04	1.8790E-06	3.6155E-06	5.0000E-06	5.0000E-06	5.0000E-06	1.5792E-06	5.0000E-07	5.0000E-07	4.0443E-07
11	6	1.8531E-04	1.8790E-06	3.6155E-06	1.0000E-06	5.0000E-06	5.0000E-06	2.3792E-06	1.0000E-07	5.0000E-07	1.2044E-06
12	6	1.0531E-04	1.8790E-06	3.6155E-06	1.0000E-06	1.0000E-06	1.0000E-06	1.5792E-06	1.0000E-07	1.0000E-07	4.0443E-07

Design C Responses				
Run	SSE	RMS	MAE	ME
1	721.6	1.1735	0.84551	-0.47597
2	722.08	1.1739	0.84614	-0.47602
3	721.91	1.1738	0.84549	-0.47599
4	721.96	1.1738	0.84581	-0.47517
5	721.58	1.1735	0.84524	-0.47556
6	721.4	1.1733	0.84544	-0.47581
7	721.54	1.1735	0.84504	-0.47685
8	722.01	1.1738	0.84607	-0.47546
9	721.77	1.1736	0.84578	-0.47569
10	722.44	1.1742	0.84657	-0.47564
11	722.13	1.1739	0.84653	-0.47455
12	721.51	1.1734	0.84551	-0.47591

Design C Steepest Descent Experiments

Steps	Porosity	Unit1	Unit2	Unit 3	Unit 4	Unit 5	Unit 6	Unit 7	Unit 8	Unit 9	Unit 10
1	7	1.5069E-04	8.1457E-06	6.9729E-06	2.8655E-06	2.7309E-06	2.5964E-06	2.0061E-06	2.4619E-07	1.2511E-07	8.0443E-07
2	7	1.5607E-04	9.2220E-06	6.9729E-06	2.7309E-06	2.4619E-06	2.1928E-06	2.0330E-06	1.9237E-07	1.0000E-07	8.0443E-07
3	7	1.6145E-04	1.0298E-05	6.9729E-06	2.5964E-06	2.1928E-06	1.7892E-06	2.0599E-06	1.3856E-07	1.0000E-07	8.0443E-07

Design C Steepest Descent Responses

Steps	SSE	RMS	MAE	ME
1	721.47	1.1734	0.84521	-0.47623
2	721.41	1.1733	0.84512	-0.47624
3	721.36	1.1733	0.84509	-0.47617

Appendix E

SUTRA FORTRAN Post-Processor File

This appendix contains the FORTRAN source code used to automatically compute the error statistics that measured the differences between the SUTRA output and the Smith-Ritzi calibration target data set. This code, named POST.FOR, was automatically called by the VMS command file in Appendix F to produce the SUTRA output report after each model execution. This code was created by Cotman (1995) and was modified to calculate error statistics using the reduced set of target values.

```
      PROGRAM POST
C     THIS PROGRAM PERFORMS POST PROCESSING OF THE SUTRA OUTPUT
C      TO DETERMINE VARIOUS ERROR STATISTICS.
      DIMENSION HBASE(600),HNEW(600)
      REAL SSE,RMS,MAE,ME,SSER,RMSR,MAER,MER
      OPEN(8, FILE='HBASE.dat',STATUS='UNKNOWN',FORM='FORMATTED')
      OPEN(9, FILE='node83.dat',STATUS='UNKNOWN',FORM='FORMATTED')
      OPEN(10, FILE='input.dat',STATUS='UNKNOWN',FORM='FORMATTED')
      OPEN(11, FILE='final.rpt',STATUS='UNKNOWN',FORM='FORMATTED')
C
      WRITE(11,90) '****************************************************
     1******************'
      WRITE(11,90) ' '
      WRITE(11,90) '              SSSS   UU  UU  TTTTTT  RRRRR     AA'
      WRITE(11,90) '             SS   S  UU  UU  T TT T  RR  RR   AAAA'
      WRITE(11,90) '             SSSS    UU  UU    TT    RRRRR   AA  AA'
      WRITE(11,90) '                 SS  UU  UU    TT    RR R    AAAAAA'
      WRITE(11,90) '             SS  SS  UU  UU    TT    RR RR   AA  AA'
      WRITE(11,90) '              SSSS    UUUU     TT    RR  RR  AA  AA'
      WRITE(11,90) ' '
      WRITE(11,90) '****************************************************
     1******************'
      WRITE(11,90) ' '
      WRITE(11,90) '                 SUBSURFACE FLOW SIMULATION MODEL'
      WRITE(11,90) ' '
      WRITE(11,90) 'Output report for R. M. Cotman''s MS thesis.  Error
     1measurements are'
      WRITE(11,90) 'compared to the steady state heads presented in R. J
     1. Smith''s thesis.'
      WRITE(11,90) ' '
      WRITE(11,90) '----------------------------------------------------
     1------------------'
      WRITE(11,90) '                              INPUT'
      WRITE(11,90) '----------------------------------------------------
     1------------------'
      WRITE(11,90) ' '
      WRITE(11,90) 'Input SUTRA data file:  filename.D5'
   90    FORMAT(1X,A)
      WRITE(11,90) ' '

         READ(10,*) ITEMP
         WRITE(11,110) ITEMP
  110    FORMAT(1X,'Porosity (Percent): ',I3)
         WRITE(11,90) ' '
      DO 30 I=1,10
         READ(10,*)TEMP
         WRITE(11,100)I,TEMP
 100     FORMAT(1X,'Hydraulic conductivity for Unit',I3,' (m/min): ',E10
     1.4)
         WRITE(11,90) ' '
  30     CONTINUE
      DO 10 I=1,524
         READ(8,*)X,Y,HBASE(I)
         READ(9,*)X,Y,HNEW(I)
 10   CONTINUE
C
      WRITE(11,90) ' '
      WRITE(11,90) '----------------------------------------------------
     1----------------'
      WRITE(11,90) '                               OUTPUT'
      WRITE(11,90) '----------------------------------------------------
```

```
     1----------------'
      WRITE(11,90) ' '
C     --------------- Sum of Squared Error (SSE) Computation -----------
      SSE=0.0
      DO 20 I=1,524
         SSE=SSE+(HBASE(I)-HNEW(I))**2
 20   CONTINUE
      SSER=0.0
      DO 60 I=57,71
         SSER=SSER+(HBASE(I)-HNEW(I))**2
 60   CONTINUE
      DO 70 I=407,415
         SSER=SSER+(HBASE(I)-HNEW(I))**2
 70   CONTINUE
      WRITE(11,120)SSE
      WRITE(11,130)SSER
 120  FORMAT(1X,'Sum of Squared Error (SSE):    ',E15.5)
 130  FORMAT(1X,'Reduced Sum of Squared Error: ',E15.5)
      WRITE(11,90) ' '
C     ------------ Root Mean Squared Error (RMS) Computation -----------
      RMS=0.0
      RMS=SQRT(SSE/524)
      RMSR=SQRT(SSER/24)
      WRITE(11,122)RMS
      WRITE(11,123)RMSR
 122  FORMAT(1X,'Root Mean Squared Error (RMS):',E15.5)
 123  FORMAT(1X,'Reduced RMS                  :',E15.5)
      WRITE(11,90) ' '
C     -------------- Mean Absolute Error (MAE) Computation -------------
      MAE=0.0
      DO 40 I=1,524
         MAE=MAE+ABS(HBASE(I)-HNEW(I))
 40   CONTINUE
         MAE=MAE/524
      MAER=0.0
      DO 80 I=57,71
         MAER=MAER+ABS(HBASE(I)-HNEW(I))
 80   CONTINUE
      DO 55 I=407,415
         MAER=MAER+ABS(HBASE(I)-HNEW(I))
 55   CONTINUE
         MAER=MAER/24
      WRITE(11,124)MAE
      WRITE(11,125)MAER
 124  FORMAT(1X,'Mean Absolute Error (MAE):     ',E15.5)
 125  FORMAT(1X,'Reduced MAE               :     ',E15.5)
      WRITE(11,90) ' '
C     -------------------- Mean Error (MAE) Computation ----------------
      ME=0.0
      DO 50 I=1,524
         ME=ME+(HBASE(I)-HNEW(I))
 50   CONTINUE
         ME=ME/524
      MER=0.0
      DO 65 I=57,71
         MER=MER+(HBASE(I)-HNEW(I))
 65   CONTINUE
      DO 75 I=407,415
         MER=MER+(HBASE(I)-HNEW(I))
 75   CONTINUE
         MER=MER/24
```

```
      WRITE(11,126)ME
      WRITE(11,127)MER
 126  FORMAT(1X,'Mean Error (ME):                ',E15.5)
 127  FORMAT(1X,'Reduced ME     :                ',E15.5)
      WRITE(11,90) ' '

      STOP
      END
```

Appendix F

VMS Command File

This appendix contains the VMS command file used to simplify the execution of the SUTRA model. The command file, named SUTRA.COM, served as an interactive interface to the SUTRA program. To invoke the command file, the user simply entered "@SUTRA" at the VMS command prompt. Upon execution, the command file would prompt the user for the porosity value and the settings of the ten hydraulic conductivities. Once these parameters were entered, the SUTRA input parameter file was automatically created, the SUTRA program was executed, and the error statistics were computed using the POST.FOR program contained in Appendix E, which also created an output report. This output report was saved as a file in the current directory and displayed to the screen for immediate review. This command file was created by Cotman (1995).

```
$write sys$output "****************************************"
$write sys$output "* SUTRA Interactive Data Input Program *"
$write sys$output "*   For Capt R. Cotman's MS Thesis     *"
$write sys$output "* Answer every question in the units   *"
$write sys$output "* shown in the ( ), using the format   *"
$write sys$output "* shown by the [ ].                    *"
$write sys$output "****************************************"
$inquire p1  "Filename of the input file you're creating [No extension]:"
$input_file = p1
$inquire p1  "Value for Porosity (percent) [xx]"
$porosity    = p1
$cnt = 0
$      open /write file unit.tmp
$      open /write file1 input.dat
$      write file "$edit template.d5"
$      write file "^Z"
$      write file "sub/po/''porosity'/w"
$      write file1 "''porosity'"
$loop:
$cnt = cnt + 1
$inquire p1  "Hydraulic Conductivity for unit''cnt' (m/min)  [x.xxxxE-xx]"
$if p1 .eqs. "" then goto finish
$string  = p1
$      write file1 "''string'"
$      write file "sub/     unit''cnt'/''string'/w"
$if cnt .eqs. 10 then write file "sub/    unit''cnt'/''string'/w"
$if cnt .eqs. 10 then write file1 "''string'"
$if cnt .eqs. 10 then goto finish
$goto loop
$finish:
$        write file "exit"
$close file
$close file1
$@unit.tmp
$rename template.d5 'input_file.D5
$      open /write file unit.tmp
$      write file "$edit sutemp.fil"
$      write file "^Z"
$      write file "sub/INPUT/''input_file'/w"
$      write file "exit"
$close file
$@unit.tmp
$rename sutemp.fil SUTRA.FIL
$cls
$cls
$write sys$output "Please wait about 15 seconds, while"
$write sys$output "the SUTRA model runs."
$run main
$run post
$      open /write file final.tmp
$      write file "$edit final.rpt"
$      write file "^Z"
$      write file "sub/filename/''input_file'/w"
$      write file "exit"
$close file
$@final.tmp
$rename final.rpt 'input_file.RPT
$del/noconfirm input.dat;*
$del/noconfirm unit.tmp;*
```

```
$del/noconfirm final.rpt;*
$del/noconfirm final.tmp;*
$pu sutra.fil
$ty 'input_file.RPT
$write sys$output "You're SUTRA model has run.  The "
$write sys$output "output report is in the file named:"
$write sys$output "''input_file'.RPT"
$exit
```

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[redacted]

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March, 1996

3. REPORT TYPE AND DATES COVERED
Master's Thesis

4. TITLE AND SUBTITLE
A RESPONSE SURFACE METHODOLOGY APPROACH
TO GROUNDWATER MODEL CALIBRATION

5. FUNDING NUMBERS

6. AUTHOR(S)
Jeffrey B. Rowland, 2nd Lieutenant, USAF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Institute of Technology
2750 P Street
WPAFB, OH 45433-6583

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/GOR/ENS/96M-14

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFCEE/ERC
Bldg 1158
8004 Chenault Rd
Brooks AFB, TX 78235-5359

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This thesis examined the effect of parameter bounding, a reduced data set, and data enrichment techniques on a response surface methodology (RSM) approach to groundwater model calibration. The four phases of the study included a calibration using a very dense data matrix, a calibration using a sparse calibration matrix, an evaluation of several data enrichment techniques, and a calibration using a data matrix enlarged with the use of the best enrichment technique. All calibrations were conducted using only a first order approximation to the response surface and with bounds placed on the input parameters. The first two calibrations using the dense and sparse data sets produced calibrated models which were very similar and very accurate. This led to the conclusion that reducing the size of the data set did not seriously degrade the calibration. The third calibration produced using the enriched data set produced results which were not as accurate as the first two calibrations and it required more calculations. Also, it was discovered that the use of a screening design would eliminate influential model parameters. All of the calibration methods provided accurate hydraulic head values, and final parameter values which were feasible.

14. SUBJECT TERMS
Parameter Estimation, Model Calibration, Response Surface Methodology

15. NUMBER OF PAGES
118

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT
UL