THE
AUTOMATED HYDROGEOLOGIC SYSTEM:
DESCRIPTION AND APPLICATION

A THESIS
SUBMITTED TO THE DEPARTMENT OF APPLIED EARTH SCIENCES
AND THE COMMITTEE ON GRADUATE STUDIES
OF STANFORD UNIVERSITY
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

BY
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FEBRUARY 1982
I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of MASTER OF SCIENCE.

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ABSTRACT

The Automated Hydrogeologic System is a network of computer programs designed to automate many of the data processing tasks of the hydrogeologic modelling investigation. These programs reduce the number of steps in the modelling investigation requiring user action from seven to three. Areas in which automation is introduced include those of data entry, parameter estimation, data manipulation, and results presentation. The automation of the estimation procedure for mapped continuously varying parameters is one of the most important features of the system. This task is accomplished through use of the digitizer and a spatial analysis package. Despite the emphasis on automation, the user review and modification process is stressed as a means by which subjectivity can be injected into the investigation. The Automated Hydrogeologic System is thus seen primarily as a time saving tool, not as a way of removing subjectivity from the modelling process.

The heart of the Automated Hydrogeologic System is a digital groundwater model. The U.S.G.S. two-dimensional groundwater model (Trescott et al., 1976) is initially selected for use in the automated system. Later, in order
to meet the requirements of the northeastern Illinois study area, the U.S.G.S. model is modified to account for the effects of aquifer layering. This modified model, called the Modified Trescott Model, still solves the two-dimensional groundwater flow equation. However, modifications have been made so that changes of head with time are also a function of the vertical geologic variation in the aquifer system. A hypothetical island aquifer is set up to validate the model in order to ensure that no errors were produced as a result of model modification.

The Cambrian-Ordovician Aquifer system of northeastern Illinois is used to assess the capabilities of the Automated Hydrogeologic System in an actual modelling investigation. This aquifer consisting of a series of hydraulically connected sandstone and dolomite units is modelled as a two-dimensional flow system with vertical variations in horizontal hydraulic conductivity. In order to calculate the horizontal hydraulic conductivities of the various units, a pre-development, steady state scenario is set up with the conductivities being subject to change during inversing. After repeated cycling through the inversing loop, a satisfactory, pre-development, steady state piezometric surface is obtained. This surface closely approximates the estimated historical water levels and is defensible in a hydrologic and geologic sense.
Though the resulting horizontal hydraulic conductivity distributions are of limited usefulness, the modelling of this aquifer system clearly demonstrates the advantages of using the Automated Hydrogeologic System in modelling investigations in hydrogeology.
ACKNOWLEDGEMENT

I would like to thank numerous people for helping nurture this project through its development. First and foremost, I would like to express my gratitude to my advisor, Dr. Irwin Remson, not only for his encouragement at all points in the project, but also for his understanding that knowledge of the Chinese language is a prerequisite for hydrogeologic studies. Without his aid and willingness to allow exploration of new areas, this research would never have been pursued.

Two men who played key roles in the research leading to the Automated Hydrogeologic System, Dr. Steven M. Gorelick and Richard A. Roth, are also deserving of thanks and recognition. Though the role of Dr. Gorelick was limited to that of a casual commentator, his comments, in the initial phases of the project, triggered the thoughts which led to the final product. Mr. Roth, on the other hand, played a more concrete role aiding my exploration of the strange new world of digitizers, bootstraps, and binary oneness. I gratefully thank Professor Ronald J.P. Lyon for allowing me to do all digitizing portions of my work at the Stanford Remote Sensing Laboratory. Union Oil, the United
States Geological Survey, the United States Bureau of Mines, Kerr McGee, and the United States Bureau of Land Management must also be acknowledged for their financial support of the Stanford Remote Sensing Laboratory and thus that portion of my work. Peter Davies, my intrepid officemate, must also be thanked for his helpful drafting advice.

Though the main focus of this project was on the Automated Hydrogeologic System, I would also like to take this opportunity to express my thanks to several people who aided my research in northeastern Illinois. Adrian Visocky and Robert T. Sassman of the Illinois State Water Survey are especially deserving of recognition. Both men gave freely of their time and records, aiding me in solving several difficult problems. Robert Shedlock and Dean Mades of the United States Geological Survey also were of a great help in supplying me with needed data and advice.

Finally, I would like to thank my parents for giving me a love of reading, a motivation to pursue an advanced degree, and, above all, a sense of humor that never allows me to take myself too seriously.

James Johnson Butler, Jr.
Stanford, California
11/25/81

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INTRODUCTION

The decades following the advent of the digital computer have witnessed an amazing movement toward utilization of the computer for serious scientific investigations as well as for more mundane data processing. The field of hydrogeology has not been exempt from this trend. The computational and storage capabilities of the computer in conjunction with various numerical techniques have given rise to digital groundwater models, computer programs capable of solving the partial differential equations of groundwater flow on an aquifer-wide basis. These models have enabled the hydrogeologist to expand his range of quantitatively studied systems from the analytically approachable, homogeneous or simple heterogeneous systems of one or two dimensions, to complex heterogeneous systems in three dimensions. In addition to this development, the computer has allowed the hydrogeologist to markedly improve his data management and processing capabilities. However, especially in the data processing sector, much work still remains before the hydrogeologist can fully realize the potential worth of his digital ally. The purpose of this paper is to describe a first step toward fuller utilization of the digital
computer in the field of hydrogeologic data processing.

This paper will describe a network of computer programs, known as the Automated Hydrogeologic System, which the author has assembled with the aim of significantly reducing the time normally spent in data handling in hydrogeologic modelling investigations. The report will consist of four chapters. The first chapter will be a relatively detailed description of the network of programs comprising the Automated Hydrogeologic System. Step by step description of programs will be kept to a minimum. Program codes and documentation can be found in the included appendices. The second chapter will consist of a rather thorough look at one of the keypoints of the network – the digital groundwater model. The specific model utilized by the system, an already developed program which the author extensively modified to meet conditions faced in his study area, will be described and its validation process reviewed. The third chapter will be a description of a study in which the network was applied to an aquifer system in northeastern Illinois. The details of the investigation and the results of the mathematical modelling are of secondary importance. They will be used primarily to reveal the potential of the assembled network, rather than to exactly portray the subsurface flow system. The paper will conclude with a brief summary and a final
assessment of the capabilities and limitations of the Automated Hydrogeologic System.
CHAPTER ONE

THE AUTOMATED HYDROGEOLOGIC SYSTEM

1.1 INTRODUCTION

The main topic of this chapter will be the development of the Automated Hydrogeologic System as a timesaving device in hydrogeologic modelling investigations. For the purpose of this chapter, the assumption will be made that a mathematical model of the groundwater flow system has already been developed. The discussion will focus on the steps in the investigation following model formulation. The steps of the traditional hydrogeologic investigation will be outlined and then the automated network presented. Areas in which automation will be introduced include those of data entry, parameter estimation, data manipulation, and results presentation. The automation of the parameter estimation procedure will be emphasized as it is undoubtedly the most significant feature of the system.

1.2 HYDROGEOLOGIC MODELLING

Before a digital groundwater model can be used for prediction of aquifer behavior, it must undergo a specification process in which it is calibrated to the
exact physical situation being faced. Calibration is normally accomplished by modelling the system over a period for which data are available. The results are then checked against the available historical records and necessary adjustments in model parameters are performed. Only after completion of this calibration is the model truly ready for use in quantitative studies of a particular groundwater system.

Under traditional modelling investigation practices, calibration consists of at least eight significant steps.

1. Gather data.
2. Contour continuous parameters.
3. Estimate parameter values at grid nodes.
5. Model operation.
6. Presentation of Results.
7. Model Verification.
8. Manage Groundwater System.

The network of computer programs assembled in this report, known as the Automated Hydrogeologic System, greatly reduces the number of these steps requiring user action. In the following section, the procedures of the traditional modelling investigation will be examined. Following this brief examination will be a lengthy discussion of the automated network. The sequential discussion of the two modelling approaches will hopefully aid the reader in understanding the advantages of automation.
1.3 TRADITIONAL APPROACH TO HYDROGEOLOGIC MODELLING

The main purpose of the data gathered in the first step of the investigation is to assign values to the set of parameters used in the mathematical description of the flow system. This parameter set consists of parameters of both a continuous and discontinuous form. The goal of the initial phase of the investigation is to transform these evaluated parameters into a form amenable to digital processing.

Digital groundwater models represent the continuous body of the aquifer by a network of discrete points. The arrangement of this network is a function of the specific numerical scheme used to approximate the partial differential equation of flow. Often this network is of a rectangular grid form. In this case, values for the model parameters are entered at each intersection of the grid, known as the grid node, and computer solution of the discretized groundwater flow equation follows.

The map point locations of the available data normally do not coincide with the nodes of the rectangular grid. Thus, one must extrapolate from the available data points to obtain parameter values at the requisite grid nodes. This extrapolation is usually done in a two-step procedure. The first step involves spatial contouring of the data, a
process which enables the modeller to define the continuous distribution of a parameter from the available discrete points. The hydrogeologic knowledge and intuition of the groundwater modeller often results in this process being somewhat subjective. This subjectivity, however, can produce a more realistic depiction of the distribution than would be possible using only the standard linear averaging rules of contouring.

Once a contour map of a needed parameter has been produced, a grid is superimposed over the map, and values of the parameter are estimated at each grid node. In theory, these values are estimates of the average value of the parameter in a defined area surrounding the grid node known as the grid cell. Obviously, this contouring and estimation process is suited only for continuously varying parameters. Parameters of a discontinuous form are handled by a simple summation of all available data in each grid cell.

Once all information needed for the groundwater model has been obtained, the transformation of these data into a form compatible with computer processing must commence. This transformation of the written word into the binary one is not a trivial task. For example, a grid system consisting of 60 columns and 60 rows, called a 60 by 60
grid, would require 3600 grid cells of information for each model parameter. In situations where time or support backup is inadequate, this mass of data could prove untenable. The task of actually processing the data into a machine readable or binary form is normally done by keypunching of cards or by direct entry onto magnetic tape or disk through a typewriter terminal.

Given that the necessary format rules have been followed, utilization of the data by the groundwater model can commence. While a detailed consideration of groundwater models will not occur at this point, ample discussion will take place during the second chapter of this report.

Regardless of the specifics of program operation, the output will normally consist of the computed hydraulic head distribution resulting from the given inputs. These results, however, in their initial numerical form, are often fairly meaningless to the hydrogeological practitioner. A further processing step is required to take the results from cryptic printouts to a more meaningful form. This processing step usually consists of plotting contour maps of the hydraulic head distribution, graphing well drawdown versus time curves, and the like.
The groundwater modeller often discovers upon analysis of his results that the computed distribution of heads in certain portions of the study area is not as the available historical data suggests it should be. Since there is a substantial degree of error inherent in the inputted parameters, the normal procedure for correcting this discrepancy is a return to the estimation phase and a re-estimation of the parameters thought to be responsible for the difference. Though these extrapolated parameters are often the propagators of the error, the hydrogeologist must keep in mind that certain approximations made during the mathematical description of the flow system can also produce marked discrepancies between modelled and historical water levels.

Once the necessary changes have been accomplished, the model is rerun using these new conditions. Often this process of model running, results comparison, and parameter re-estimation is repeated numerous times before satisfactory agreement between the modelled and historical water levels is obtained. This portion of the model calibration process, known as the inversing* loop, will be

* By strict definition, the inverse method is the direct solution of the flow equation for the distribution of the hydraulic parameters. However, in common usage and in this paper, the term is also taken to mean the process of adjustment of parameters to obtain a calibrated model.
discussed in a later section.

Given a groundwater model which has been calibrated to a certain flow system, the hydrogeologist is ready to assume his role as aquifer manager. By using the model as a predictive tool, the hydrogeologist is able to greatly improve his capability to assess future aquifer behavior. Areas in which estimates of an almost mystical quality had been the rule, now become relatively accessible to the groundwater basin manager if the requisite data base is available.

1.4 AUTOMATED APPROACH TO HYDROGEOLOGIC MODELLING

Close examination of the steps of the traditional modelling investigation reveals marked inefficiencies in the procedure. Time and effort spent in data processing and preparation dominate the investigation process resulting in relatively little time spent in serious analysis of aquifer behavior. From the contouring of continuous parameters, to estimation of nodal values, to computer entry, to production of user meaningful results, to the inversing process, relatively mindless data processing dominates the tasks associated with the modelling investigation.
The automated network attempts to minimize the role of the modeller in this data processing by reducing the number of steps in the modelling investigation requiring user action from eight to three.

1. Gather data.
2. Automation with user interaction.
3. Manage groundwater system.

The second step is actually subdivided into the following procedures.

1. Computer entry.
2. Parameter estimation and data processing.
3. User modification.
4. Model operation.
5. Model verification.
6. Presentation of results.

Note that the gathering of data still largely remains outside the bounds of automation. The advent of large data banks linked to national computer networks is a significant step toward computer utilization in this field. However, the large amount of inertia which must be overcome to successfully implement such a system will undoubtedly result in the present situation existing for years to come.

One of the key points of the automated package is the manner in which it eases the pain of handling continuously varying parameters. For hydrogeologic modelling purposes, parameters of a continuously varying form are normally those describing hydraulic head, transmissive and storage properties, and formation thicknesses. Depending on the situation, other factors such as precipitation,
temperature, and solute concentration can also be important.

1.41 Data Forms

The automated system does away with the tedious contouring phase of the traditional modelling investigation by direct entry of the data into the computer. In order to accomplish this task, the data must be in a form amenable to automated processing. Data not meeting the prescribed requirements must be altered to the correct form in an additional pre-entry phase. For reasons which will become clear shortly, the data must be keyed to an X-Y Cartesian coordinate system.

There are three data forms which can easily be transformed to meet this requirement. These three forms being data which have already been plotted on topographic or geologic maps, data keyed to longitude and latitude, and areal specific data keyed to local features. Data already plotted is transformed into a Cartesian coordinate form through use of a digitizer, a procedure discussed in section 1.421. Data keyed to longitude and latitude is processed into a X-Y form by means of the programs discussed in section 1.411. Areal specific data is handled by setting the major feature of the area as the origin and
assigning X-Y coordinates to surrounding points with respect to this central feature.

1.411 Data Forms - Discussion

Care should be taken so that maps of differing projections do not become intermixed in the same modelling investigation. If such problems do arise, the longitude and latitude of the discrete points should be noted and the data entered in that form. Data keyed to longitude and latitude can then be transformed into a map of the desired projection through programs developed by Stanford geophysicists. (D. Engelbritson, 1981, personal communication) These programs, not yet integrated into the automated system, enable the user to freely transfer between maps of differing projections.

Mention should be made of data keyed to the township and range coordinate system, a common practice in the western portion of the United States. All data of this type must be transformed into one of the prescribed forms before computer entry due to distortions in the township and range system.

1.42 Automated Network
FIGURE 1 - Flowchart of Automated Hydrogeologic System. Note the network has been segmented according to the steps in the automated modelling investigation.
With the data defining the distribution of the continuous members of the parameter set in the correct form, entry into the network of computer programs which makes up the Automated Hydrogeologic System can proceed. Figure 1 is a flow chart illustrating the programs comprising the automated network. The network has been segmented as shown and will be discussed in that order.

1.421 Computer Entry

The computer entry process comprises the first phase of the automated network. Data assigning values to either unmapped continuous parameters or discontinuous parameters are entered onto the computer through keypunching or typing at a terminal. Data assigning values to mapped continuous parameters are entered using a digitizer. This introduction of the digitizer into the hydrogeologic modelling investigation is one of the key features of the automated package.

1.4211 Computer Entry with Digitizer

The digitizer assigns a location in X-Y coordinates to every mapped data point. With an accuracy of one-two hundredth of an inch, the digitizer is capable of discriminating in areas of very high data density. Since
it only assigns X-Y coordinates to each point, further software had to be developed to allow a third coordinate to be recorded along with the spatial location. Programs were designed to record the spatial coordinates of any data point and its magnitude. The programs accomplishing these tasks were called Super Hydra and Super Buth (Butler-Roth) respectively. Both programs along with sufficient documentation can be found in Appendix A.

The Super Hydra program is used to enter data of a contoured form. Ignoring the extra features common to both Super Hydra and Super Buth, the program begins operation by requesting that the user enter the magnitude of the contour line to be digitized. The user then proceeds to digitize that contour line signalling when he is finished by punching a designated cursor key. Continuing in this manner, all desired contour lines are transferred onto the computer as a series of discrete points in a Cartesian coordinate system.

The Super Buth program is used to enter data of a discrete point form. Though somewhat more involved than its companion, Super Hydra, due to the necessity of recording a separate magnitude for each point being digitized, the program maintains simplicity by using an ordinary ruler to accomplish its tasks. Excluding the
features common with Super Hydra, the program operation can be summarized in four steps.

1. Normalizing ruler to parameter extremes.
2. Calculation of parameter values associated with each subdivision of the ruler.
3. Digitizing mapped point to record spatial coordinates.
4. Digitizing appropriate line on ruler to record magnitude of mapped point.

The precision of the procedure depends greatly on the range in the magnitude of the mapped parameter. In most instances when hydraulic heads or formation thicknesses are to be recorded, a precision of at least half a foot can be achieved. When dealing with maps of transmissivity, however, variations in both aquifer thickness and transmissive properties can result in the data being spread over quite a wide range. The precision of the task may decrease substantially in these situations.

1.42111 Computer Entry with Digitizer - Discussion

The extra features common to both the Super Hydra and the Super Buth programs allow the user to take into account the orientation of the map on the digitizing tablet, the scale of the map, and the range of digitized values for each coordinate. The interactive nature of both programs enables them to be easily utilized by a person unfamiliar with the details of their workings.
1.422 Parameter Estimation and Data Processing

Once the data have been recorded onto disk or tape files, the modeller is ready to move to the main body of the automated network, the parameter estimation and data processing stage.

The reason for keying data defining the distribution of continuously varying parameters to a Cartesian coordinate system is that the computer utilizes such data to automatically perform the parameter estimation phase of the modelling investigation. A rectangular grid is superimposed over the discrete data points and parameter values at each of the grid nodes are automatically estimated. A process normally taking on the order of days is reduced to a few seconds of CPU time!

The group of programs responsible for this dramatic time savings is known as a spatial analysis package. A spatial analysis package is "a computer contouring and graphics display system." (Sampson, 1978, p.i) The package used in this study was a product of Robert Sampson of the Kansas Geological Survey called SURFACE II (Sampson, 1978).

This spatial analysis package was primarily developed to display spatially distributed data in a variety of forms ranging from simple two-dimensional contour maps to pseudo
three-dimensional transect plots. The key feature which allows the use of the package for the parameter estimation task is the method by which the system creates its spatial plots. The SURFACE II package takes irregularly distributed points as input and from these plots contour maps and the like. In this process, a rectangular grid is automatically superimposed over the data and values are estimated at each grid node. The contouring then takes place through interpolation between adjacent grid nodes. By intercepting the process at the completion of the node estimation procedure, automation of the parameter estimation task is achieved with only a minimum of effort. In addition, a grid network can be inserted into the system at this point and all graphics features of the spatial analysis package utilized. Several other useful features of this package will be discussed later in the chapter. It should be emphasized that the data must be keyed to a Cartesian coordinate system if any of the tasks of this spatial analysis package are to be performed.

Once the grid of a user-specified size has been automatically superimposed over the data, the SURFACE II package allows the nodal estimation process to be handled in any one of three ways. The three techniques of parameter estimation are distance weighted averaging, trend surfaces, and kriging. A description of these methods is
found in Sampson(1978).

Regardless of the specific method chosen, the end result is an estimate of the needed parameter at each node of the grid network. The initial data points thus have been extrapolated outward to form a continuum from which another series of discrete points has been selected.

Some mention should be made of other portions of the SURFACE II package which can be used in conjunction with the parameter estimation procedures. Within the SURFACE II package there are routines which allow the user to perform arithmetic operations on the estimated values. These routines can be utilized to obtain estimates of formation thicknesses by subtraction of nodal estimates of the surfaces bounding the formation. Thus the user need not search for just one specific data set when trying to define the distribution of a certain parameter, other data sets often can be manipulated to obtain the desired information.

It should be mentioned here that the form in which the data are processed by the components of the spatial analysis package requires several small programs to convert from binary to formatted results and back when user review is necessary. One example of such a program, which converts from binary to formatted results, titled Giveme,
can be found in Appendix A.

1.423 Remarks on Subjectivity - An Important Hydrogeological Tool

The data which have thus been transformed are essentially ready for entry into a digital groundwater model. Minor amounts of processing must be done to ensure proper format, but otherwise no major obstacles remain. However, there is still one pressing issue which must be addressed before proceeding further with discussion of the automated network. All steps to this point have been completely automated. The hydrogeologist has not had an opportunity to impinge his qualitative feelings onto the process. Though many might argue that the whole purpose of automation is to do away with this subjectivity, the author felt that the experience and knowledge that the groundwater geologist has concerning the hydrogeology of an area, though difficult to evaluate, should play a role in the parameter estimation process. The automated system was thus envisioned primarily as a time-saving tool, not as a way of removing subjectivity from the modelling process.

1.424 User Modification

The user modification step involves examination of the
results at the completion of the grid node estimation phase. These results can take the form of line printouts or plots produced from the graphics routines of the system analysis package. If the results are not as the modeller envisioned they should be, due either to poor estimates in areas of low data density or to the inability of the estimation procedure to take into account the qualitative knowledge of the modeller, they should be modified at this point. Wholesale modifications can possibly indicate that manual contouring and gridding would be a better approach for that specific situation. The assumption here is that normally there will be relatively small differences between the results of the manual and automatic procedures, so the dramatic time savings would recommend the latter course of action. The automated node estimation process should thus be considered a rapid first step with the user modification procedure a fine tuning of the automated estimates.

1.425 Model Operation

With completion of the user modification step, the system moves to the modelling phase of the network. Before the data can be utilized by the model, however, they must be transformed into the correct format. A small program, known as Condor, which performs this task in conjunction with the modified version of the two-dimensional
groundwater model of the United States Geological Survey (Trescott et al., 1976) is included in Appendix A.

Detailed discussion of the nature of groundwater models will be deferred to Chapter Two. It should be mentioned here, however, that in this study the automated network, though designed to allow the user to choose from a number of different models depending on the exact aquifer conditions, solution techniques, and approximation schemes desired, was actually only utilized in conjunction with the U.S.G.S. model (Trescott et al., 1976) and its modification.

1.426 Presentation of Results

Reference was made earlier to the form of the simulation results and the problems involved with it. The countless lines of cryptic printout produced by many of the groundwater models must be transformed into a more readily analyzable form. This transformation is performed by utilizing the graphics of the spatial analysis package to produce representations of the two-dimensional distribution of the results either as contour maps or perspective block diagrams. In addition, plotting routines of the automated network which are separate from the spatial analysis package can be utilized to produce time drawdown curves and the like. In this report, these plotting routines were
part of the TOPDRAW package (Stanford Center for Information Processing, 1978) developed at the Stanford Linear Accelerator Center. Most computers of a mini- or mainframe scale will have such a plotting package.

1.427 Model Verification

In order to be used as an effective, predictive tool, the groundwater model must be verified against real data. This verification process involves starting with known initial conditions and attempting to reproduce known final conditions through model simulation. Naturally, this process is quite area and aquifer specific. However, once a groundwater model has been verified, it is considered calibrated and can be used as a valid predictive tool within its area and aquifer constraints.

Not surprisingly, the automated network plays an important role in this verification procedure. In these cases, the historical water level maps are also digitized and undergo the grid node estimation process. When a model run is complete, the results are automatically compared to these historical values and contour maps of their differences produced. Maps of both piezometric surfaces can also be produced, thus allowing the modeller to make the comparison manually. If the computed head values are
not in agreement with the historical water levels, the
inversing loop is entered. The purpose of this loop is to
readjust the values of certain of the input parameters in
order to improve the agreement between historical data and
computed results. A general quantitative definition of
this agreement is difficult as it is a function of the
scale and purpose of the modelling study.

1.4271 Parameter Adjustment

The parameter adjustment process can be handled with
varying degrees of automation. The primary method in
practice is the non-automatic re-estimation and adjustment
procedure based on hydrogeologic reasoning. Through
examination of the response of the model to the given
inputs, a knowledge of the specific aquifer system under
study, and a thorough understanding of the principles of
fluid flow in porous media, the hydrogeologist is able to
make knowledgeable, though admittedly subjective,
judgements concerning parameter re-estimation. Given the
normal posing of the modelling problem and the usual data
availability, the targets of the re-estimation process are
generally the hydraulic parameters; the
transmissivity(hydraulic conductivity) and, to a lesser
extent, the storativity(specific yield). Other parameters
can also be subject to this adjustment process, but
generally the modeller has a fair degree of confidence in these and prefers to focus on the always problematic hydraulic parameters.

Regardless of which parameter is under scrutiny, the manual re-estimation process is often quite time-consuming. However, due to the importance of subjective judgement in parameter readjustment, the user should not look to blindly automate. Automated operation of this procedure can be considered, but the modeller must strive to balance the gains in automation versus the losses in knowledgeable insight.

A multitude of techniques have been developed to automate this inversing procedure. Though this paper will not consider any procedures totally devoid of subjectivity, the range of possibilities is still quite large. The linear programming approach is one class of methods which has often been applied toward this problem. By embedding the groundwater flow equation and subjective constraints on relevant parameters into a linear program, the modeller can obtain a purported optimal set of parameters for his problem. Questions have arisen concerning the uniqueness of this "optimal" solution, so the future of this approach is rather cloudy. A variety of statistical based techniques such as the earlier mentioned kriging and
variations of the least squares method also have been
developed which allow the user to input his knowledge of
the system into the computations. For a thorough
discussion of these and other possible procedures, the
works of Bear (1980), Neuman (1973), Cooley (1977), and
Yeh (1975) are recommended.

The automated package detailed in this report relied
on the manual method of inverting. Nevertheless, the
mechanics of inserting most of the more automatic inverting
procedures into the network are quite simple. If the
decision to automate is made, the modeller must keep in
mind the earlier emphasized danger of losing knowledgeable
insight as the cost of automation.

1.5 DISCUSSION

Though the task of the automated system has been
fulfilled with the attainment of a calibrated model, the
network should not be forgotten. The automated package
will also prove beneficial when using the model for
predictive purposes. Though no calibration is to be done,
the automated data entry, processing, and display
operations will still be enormous time savers for the
hydrogeologic modeller.
Before leaving the discussion of the Automated Hydrogeologic System, a few final points concerning the limitations of the automated network should be mentioned.

1.51 System Limitations

Besides the requisite data form, there are several other significant limitations of the automated network. All involve the parameter estimation portion of the spatial analysis package. Though knowledge of these limitations is important, they should not be considered to jeopardize the usefulness of the automated network.

The most serious limitation of the system is that the SURFACE II package estimates the value of the parameter at the grid node instead of estimating the average value of the parameter in the grid cell as required by groundwater models. In most cases, the parameter value at the center of the grid cell, the node, can be assumed to equal the cell average. This is not always the case, so, in certain situations, care must be taken to modify the automatically estimated values.

The SURFACE II spatial analysis package also requires the use of a grid of constant spacing in each dimension.
The SURFACE II spatial analysis package also requires the use of a grid of constant spacing in each dimension. Since grids of irregular spacing are widely used in modelling investigations, this is a serious limitation. However, this limitation can be overcome by modification of the SURFACE II package or by setting the grid spacing at a minimum value and deleting all unneeded columns and rows in the user modification step.

A third limitation involves the earlier mentioned data density problem. Areas of low data density can cause the parameter estimation process at neighboring grid nodes to be incorrect. This is dependent upon the exact estimation scheme being used. Experimentation is necessary to discover the limitations of the specific scheme. Once aware of these data density limitations, the modeller should utilize the user modification step to correct the resultant errors.
CHAPTER TWO

THE MODIFIED TREScott MODEL

2.1 INTRODUCTION

With completion of the discussion of the Automated Hydrogeologic System, the scope of the paper changes from a general overview to a relatively detailed examination of one of the key components of the automated network, the digital groundwater model. This inquiry into the nature of groundwater models will begin with a brief subject overview before focusing in on a modified form of the United States Geological Survey groundwater model (Trescott et al., 1976) as a vehicle for further discussion. The justification, modification, and subsequent validation of this model will be examined in depth in order to give the reader an understanding of the considerations involved in model development and utilization.

2.2 DIGITAL GROUNDWATER MODELS

Digital groundwater models are computer programs which, when combined with data, either collected in the field or inferred based on geologic judgement, enable the partial differential equation of groundwater flow to be
solved under a wide range of conditions. The more advanced of these models allow the hydrogeologist to account for all but the micro-scale complexities of his studied system. Though numerous groundwater models have been developed, most modellers in hydrogeology would agree that only two, the Illinois State Water Survey model (Prickett and Lonnquist, 1971) and that of the United States Geological Survey (Trescott et al., 1976), have gained widespread acceptance. In this report, all work was done using the U.S.G.S. model (Trescott et al., 1976) or its modification.

2.21 Trescott Model

The U.S.G.S. model (Trescott et al., 1976), henceforth to be called the Trescott Model, essentially solves the two-dimensional form of the confined groundwater flow equation (1) under anisotropic and heterogeneous conditions.

\[ \frac{\delta}{\delta x} \left( T \frac{\delta h}{\delta x} \right) + \frac{\delta}{\delta y} \left( T \frac{\delta h}{\delta y} \right) = S \frac{\delta h}{\delta t} + W \]  

\( h = \) Hydraulic Head  
\( S = \) Storage Coefficient  
\( T = \) Transmissivity  
\( W = \) Source Term  
\( x,y = \) Spatial Dimensions  
\( t = \) Time

A slight modification (2) allows application to unconfined aquifers.

\[ \frac{\delta}{\delta x} \left( K \frac{\delta h}{\delta x} \right) + \frac{\delta}{\delta y} \left( K \frac{\delta h}{\delta y} \right) = S \frac{\delta h}{\delta t} + W \]  

\( K = \) Hydraulic Conductivity  
\( S_y = \) Specific Yield
Several additional features of the model allow the user to take into account effects of leakage (both transient and steady state), evapotranspiration, and a combined artesian-water table aquifer.

This model was chosen over that of the Illinois State Water Survey primarily due to their differences in solution techniques. However, the Trescott Model was also considered superior in regards to consideration of leakage through confining beds, averaging of transmissivities, and treatment of constant head boundaries.

2.211 Model Assumptions

Before the hydrogeologist can use a groundwater model for application purposes, he must understand the assumptions which have gone into the development of that particular model. An examination of the flow equations (1,2) solved by the Trescott Model reveals five major assumptions made during model derivation.

1. Two-dimensional flow field.
2. Water instantaneously released from storage.
3. Principal directions of anisotropy parallel to X and Y axes.
4. System stresses constant during each time step.
5. Wells are fully penetrating.

In addition to these, a further assumption was made that allows the continuously varying parameters to be represented as step functions.
2.22 Three-Dimensional Flow Systems

Any time a flow system which cannot easily be reduced to two-dimensions confronts the Trescott Model, problems will arise. Even the relatively simple water table aquifer-aquiclude-confined aquifer case can only be modelled if the water table remains constant during each time step.

Since the Trescott Model has limited capabilities in these circumstances, the hydrogeologist must turn to other sources when studying such situations. A three-dimensional form of the Trescott Model has been developed to simulate complex flow systems. However, such three-dimensional or pseudo three-dimensional models generally have a number of drawbacks, the most notable being their data requirements. Very rarely in modelling investigations do enough data exist to accurately portray the flow system in three dimensions. Though the hydraulic data are lacking, the data defining the geologic framework are often quite abundant. The problem thus is to figure out how to utilize the detail of the geology without overreaching the hydrologic limitations.

This problem was approached in the context of a regional study of the Cambrian-Ordovician Aquifer system of northeastern Illinois, the details of which will be
discussed in Chapter Three. In brief, the situation being faced was that of a multi-layered dolomite and sandstone aquifer. The three-dimensional geologic picture of the area was known fairly well, but the hydrologic data were essentially limited to the areal dimensions. The hydraulic potential data that were available indicated a good connection between all units with little potential difference in the vertical dimension. Though the hydraulic properties of the units appeared to differ, these differences were not considered great enough to warrant the consideration of the system as a series of alternating aquicludes and aquifers.

The Cambrian-Ordovician Aquifer system is presently in a confined state over most of the area, so its behavior could be simulated using the Trescott Model with the hydraulic conductivity being some sort of layered average. However, all indications point to a sizeable increase in the extent of the unconfined portions of the aquifer in the near future. Since one of the goals of the investigation was predictive capabilities, a model which considered the effects of layering during aquifer dewatering had to be developed.

2.23 Modified Trescott Model
The most effective manner of handling this situation was to take the Trescott Model and modify it to account for the effects of a layered aquifer system. The three-dimensional form of the Trescott Model was considered but was rejected due to the earlier mentioned data limitations and its inability to handle dewatering situations.

This modified model, henceforth to be called the Modified Trescott Model, behaves in a standard two-dimensional mode when dealing with a confined aquifer, i.e. potential varying only in the horizontal dimensions, system transmissivity being an average of that of the individual layers, etc. If dewatering occurs, the potential continues to vary only in the horizontal dimensions and the transmissivity is still a layered average. In this case, however, the hydraulic conductivities used to calculate the transmissivity are considered to vary, albeit in a step-wise fashion, in the vertical dimension.

The equation solved by this modified program is that given below (3).

\[
\frac{\delta}{\delta x}(K_{xx} \frac{\delta h}{\delta x}) + \frac{\delta}{\delta y}(K_{yy} \frac{\delta h}{\delta y}) = S \frac{\delta h}{\delta y} + W \quad (3)
\]

\[
K_T = \frac{K_1 B_1 + K_2 B_2 + \ldots + K_n B_n}{B_1 + B_2 + \ldots + B_n} \quad (4)
\]

- \(K_T\) = Hydraulic Conductivity of Layer \(i\)
- \(K_i\) = Hydraulic Conductivity of Layer \(i\)
- \(B_i\) = Saturated Thickness of Layer \(i\)
The expression for the average horizontal hydraulic conductivity of the layered medium (4) is the simple average recommended by Bouwer (1978). Note the similarity of equation (3) to the unconfined equation of the Trescott Model (2). Except for their manner of considering hydraulic conductivity, they are the same equation. The similarity of the two models must be emphasized; the modified version has no radical changes. The modifications are, for the most part, simply an extension of the algorithms used in the combined artesian-water table case of the Trescott Model to a multi-layered aquifer. The same algorithms are used to model the piezometric surface moving from one layer to another within the aquifer as are used to model the piezometric surface moving from an aquiclude to the aquifer itself. A detailed discussion of these modifications is not of general interest. Interested readers are referred to the program listing in Appendix A.

In summation, the Trescott Model was modified so as to be able to account for the effects of hydraulically connected layers of differing hydraulic properties on aquifer dewatering. The Modified Trescott Model is still strictly two-dimensional; the equation being solved is that of a two-dimensional groundwater flow system. However, modifications have been made so that changes of head with time are also a function of the vertical geologic
variation in the aquifer system.

2.231 Validation of Modified Model

Before the modified model can be applied to a real aquifer system, it must be validated. This process of model validation consists of formulating a simple, hypothetical aquifer in which the results of the simulation of the Modified Trescott Model can be compared to an analytic solution or to the results of the simulation of an earlier validated digital model. This comparison is used to ensure that no errors, due either to carelessness or incorrect representation of the physical processes, have occurred during model modification. Due to the complexity of the layered situation, no useable analytic solution could be found. Thus, the Trescott Model was selected for use in the validation process. Since the Modified Trescott Model is of a two-dimensional form, by careful posing of scenarios, the Trescott Model could be used as a valid "tool" for model validation.

Two scenarios were devised for validation purposes. The first scenario was such that both the regular and modified versions of the Trescott Model would produce the same results. In this way, careless coding or a failure to accurately represent the flow processes would become
apparent. The second scenario was posed so as to produce differing results between the two models in order that a qualitative check based on theoretical predictions could be performed. The results of this scenario would reveal the errors introduced when the unmodified Trescott Model is used to simulate layered conditions.

The hypothetical aquifer used in the validation process is shown in Figure 2. Figure 2A is an areal view of the system with Figure 2B being a cross-sectional look along line C-C'. An aquifer of rectangular surficial dimensions was chosen to allow the grid network, shown in Figure 3A, to be easily superimposed over the system without invoking boundary approximation problems. A line of no flow nodes has been added to each side of the grid in order to prevent model computations from passing out of the area of interest. Figure 3B shows the equation to be solved for this system with its initial and boundary conditions. Note that in addition to the assumptions of the Trescott Model discussed earlier, this hypothetical aquifer is also isotropic in the horizontal dimensions, is bounded by constant head boundaries, has horizontal layers of constant thickness, and is characterized by an absence of leakage, evaporation, and areally distributed recharge.
FIGURE 2A - Areal view of hypothetical aquifer used in model validation. C-C' is the line of the cross-section in Figure 2B.
FIGURE 2B - Cross-section along line C-C' of hypothetical aquifer used in model validation. Impermeable bedrock is assumed to underlie the bottom layer.
FIGURE 3A - Rectangular grid used in validation scenarios. Note that no flow nodes bound grid in order to prevent model computations from moving out of the area of interest.
Equation For Validation Scenarios

\[ \frac{\partial}{\partial x}(K_i \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(K_i \frac{\partial h}{\partial y}) = S_y \frac{\partial h}{\partial t} + W \]

**Boundary Conditions:**
- \( h(x,0,t) = H \)
- \( h(x,1,t) = H \)
- \( h(0,y,t) = H \)
- \( h(1,y,t) = H \)

**Initial Conditions:**
- \( h(x,y,0) = H \)

in which

\[ K_T = \frac{K_1 B_1 + K_2 B_2 + K_3 B_3 + K_4 B_4}{B_1 + B_2 + B_3 + B_4} \]

- \( K_i \) = Hydraulic Conductivity of Layer \( i \)
- \( B_i \) = Saturated Thickness of Layer \( i \)

- \( K \) = Hydraulic Conductivity of Aquifer for Regular 2-D Trescott Model
- \( K \) = Hydraulic Conductivity of Aquifer for Modified 2-D Trescott Model

- \( h \) = Hydraulic Head
- \( S_y \) = Specific Yield
- \( W \) = Recharge/Discharge Well
- \( x,y \) = Spatial Dimensions
- \( t \) = Time

**FIGURE 3B** - Equation solved in validation scenarios. Note that the total horizontal hydraulic conductivity varies depending on the specific groundwater model used.
2.2311 First Validation Scenario

The conditions for the first scenario are given in Figure 4A. For this case, the hydraulic parameters of both the modified and unmodified forms of the Trescott Model were set equal to those of Layer A. As in the second scenario, Wells A, B, and C were treated as discharge wells with Well D being used for recharge purposes. All wells operated at constant rates during the simulation period.

The objective of this first case was to start with an initial horizontal water table five feet above the base of layer A and pump the system at a constant rate until aquifer dewatering or steady state equilibrium was achieved. Since both models had the same parameter values, they differed only in the manner in which the Modified Trescott Model performs layered computations. Figure 4B is a drawdown versus time plot of the results for node (7,4), the location of Well A. As shown in this plot, the results of the two models were equal at all times during the modelled period. Since water levels were drawn down into layer B during the simulation, the layer conversion processes are considered to have been accurately represented by the algorithms of the Modified Trescott Model.
VALIDATION SCENARIO 1

Modified 2-D Trescott Model

Case 1 Parameters

Pumpage
Well A = -4.32 cub. ft./sec.
Well B = -2.88 cub. ft./sec.
Well C = -0.72 cub. ft./sec.
Well D = 0.72 cub. ft./sec.

Hydraulic Conductivity
\[ K_1 = K_2 = K_3 = K_4 = 8.7 \times 10^{-4} \text{ ft./sec.} \]

Specific Yield
\[ S_1 = S_2 = S_3 = S_4 = 0.02 \]

Hydraulic Head
\[ H(x,y,0) = 675 \text{ ft.} \]

Formation Thickness
\[ B_1 = B_2 = B_3 = B_4 = 40 \text{ ft.} \]

Regular 2-D Trescott Model

Case 1 Parameters

Pumpage
Same as Case 1 of Modified 2-D Trescott Model.

Hydraulic Conductivity
\[ K = 8.7 \times 10^{-4} \text{ ft./sec.} \]

Specific Yield
\[ S_y = 0.02 \]

Hydraulic Head
Same as Case 1 of Modified 2-D Trescott Model.

Formation Thickness
Same as Case 1 of Modified 2-D Trescott Model.

FIGURE 4A - Definition of parameter values used in first validation scenario.
FIGURE 4B - Well drawdown versus time plot for node (7, 4) in first validation scenario.
2.2311 First Validation Scenario - Discussion

Actually, the cumulative water removed from storage was found to have been 0.00145 percent higher in the modified model simulation than in the unmodified run. This small difference was due to the layer conversion algorithms being used by the Modified Trescott Model but not by the Trescott Model during this simulation.

2.2312 Second Validation Scenario

The second scenario was used to qualitatively illustrate the errors which can appear when using the Trescott Model to simulate a layered aquifer with predominantly horizontal flow. In this scenario, two separate runs of the Trescott Model were made and then compared to the results of a Modified Trescott Model simulation.

The first of the Trescott simulations, Case 2A in Figure 5A, took place under the same conditions as in the first scenario, hydraulic conductivity and specific yield being that of layer A. The second of the Trescott simulations, Case 2B in Figure 5A, occurred with hydraulic conductivity being a simple average of the layer conductivities and specific yield again that of Layer A. The Modified Trescott simulation, Case 2 in Figure 5A, was
VALIDATION SCENARIO 2

Regular 2-D Trescott Model

Case 2A Parameters

Pumpage
Same as Case 1 of Modified 2-D Trescott Model.

Hydraulic Conductivity
Same as Case 1 of Regular 2-D Trescott Model.

Specific Yield
Same as Case 1 of Regular 2-D Trescott Model.

Hydraulic Head
Same as Case 2 of Modified 2-D Trescott Model.

Formation Thickness
Same as Case 1 of Modified 2-D Trescott Model.

Case 2B Parameters

Pumpage
Same as Case 1 of Modified 2-D Trescott Model.

Hydraulic Conductivity
K = 2.2 x 10^-4 ft./sec.

Specific Yield
Same as Case 1 of Regular 2-D Trescott Model.

Hydraulic Head
Same as Case 2 of Modified 2-D Trescott Model.

Formation Thickness
Same as Case 1 of Modified 2-D Trescott Model.

Modified 2-D Trescott Model

Case 2 Parameters

Pumpage
Same as Case 1 of Modified 2-D Trescott Model.

Hydraulic Conductivity
K x = 8.7 x 10^-4 ft./sec.
K y = 1.7 x 10^-7 ft./sec.
K z = 1.7 x 10^-4 ft./sec.
K 4 = 1.7 x 10^-5 ft./sec.

Specific Yield
S 1 = 0.02
S 2 = 0.15
S 3 = 0.05
S 4 = 0.03

Hydraulic Head
H(x,y,0) = 700 ft.

Formation Thickness
Same as Case 1 of Modified 2-D Trescott Model.

FIGURE 5A - Definition of parameter values used in second validation scenario.
of this second validation scenario for node (7, 4) are illustrated by the time drawdown curves of Figure 5B.

As a result of the unmodified Prescott simulations, Case 2A, quickly diverged from the results of the modified large drawdown simulations experienced when significant downward transmissivity was added to the hypothetical aquifer. The topmost layer of the simulated aquifer is the most permeable.

The first of the unmodified Prescott simulations, Case 2B, did not suffer these same relative decreases in transmissivity, so that state equilibrium was rapidly approached. Surprisingly, the modelling of a layered aquifer system with the Prescott Model using the hydraulic parameters of a random layer produced very questionable results.

The second of the unmodified Prescott simulations was also performed using the hydraulic parameters of the layered aquifer.

FIGURE 5B – Well drawdown versus time plot for node (7, 4) in second validation scenario.
run under true layered conditions with hydraulic parameters varying as much as three orders of magnitude. The results of this second validation scenario for node (7, 4) are illustrated by the time drawdown curves of Figure 5B.

The first of the unmodified Trescott simulations, Case 2A, very quickly diverged from the results of the modified model simulation as would be expected since the topmost layer of the hypothetical aquifer is the most permeable. As this top layer was dewatered, the overall transmissivity of the layered aquifer of Case 2 decreased markedly resulting in large drawdowns. The aquifer of Case 2A did not suffer these same relative decreases in transmissivity, so steady state equilibrium was rapidly achieved. Not surprisingly, the modelling of a layered aquifer system with the Trescott Model using the hydraulic parameters of a random layer produced very questionable results.

The second of the unmodified Trescott simulations closely approximated the results of the modified Trescott run for the initial four time steps. After the fourth time step, the significant decrease in the overall transmissivity of the layered system following the dewatering of layer A, coupled with drawdown into the least permeable unit, layer B, resulted in a condition which the averaged conductivities of the Trescott Model could not
correctly simulate. In cases where vertical variations in hydraulic conductivities are an order of magnitude or less, however, this averaged approach has proven quite successful.

The results of the Modified Trescott Model simulation met the theoretical expectations. An initial period of large drawdowns was experienced until significant head gradients to the bounding rivers could be established, resulting in a decrease in the amount of water being removed from storage. The sizable percentage drop in aquifer transmissivity after the dewatering of the highly transmissive Layer A, however, resulted in a renewed period of large drawdowns which led to node dewatering after twenty-seven days of pumpage.

2.2313 Validation of Modified Model - Discussion

The results of this series of validation runs are taken as proof of the ability of the Modified Trescott Model to simulate layered conditions in an aquifer characterized by primarily horizontal flow. The matching results of the first scenario indicate that no careless coding or misrepresentation of physical processes has occurred. The results of the second scenario, though admittedly of a more qualitative nature, not only show that
the Modified Trescott Model behaves as expected, but also graphically illustrate the need for a model with such capabilities.
3.1 INTRODUCTION

This chapter is concerned with the application of the automated network to an aquifer system in northeastern Illinois. A brief discussion of the geologic and hydrologic characteristics of the area will be given. Then, the actual modelling of the aquifer system will be described while stressing the role of the automated network. The results of the model application will only be briefly commented upon, as the specifics of the physical situation will not be considered paramount to the discussion. Rather, the uses and advantages of the automated network will be emphasized throughout in order to enable the reader to more fully grasp the benefits of its use in modelling investigations.

3.2 BACKGROUND

In 1864, the first deep well was drilled in the Chicago area of northeastern Illinois. The well reached a depth of 711 feet terminating in the lower portions of the
Galena-Platteville Formation, a dolomite of Ordovician age. Water flowed out of the well under artesian pressure at an estimated 200,000 gallons per day with a hydraulic head approximately eighty feet above the land surface. (Suter et al., 1959, p. 53) By 1971, 107 years later, the situation had changed quite dramatically. The solitary deep well of 1864 now had hundreds of companions pumping an estimated 150.7 million gallons per day in the eight county region surrounding Chicago. This greater than 75,000 percent increase in pumpage since 1864 had resulted in more than a 850 foot decrease in hydraulic head of the Cambrian-Ordovician Aquifer system in areas of concentrated pumpage. This came to an average decrease of greater than 7.5 feet per year. In the five years following 1971, the rate of decrease rose to nearly 12 feet per year. (Sasman et al., 1977, p.1) This figure would have been much higher except that extensive portions of the aquifer system were now being dewatered and thus, in those areas, water release was predominantly due to dewatering mechanisms rather than the pressure-driven processes of confined aquifers. At present, in the early nineteen eighties, with significant decreases in pumpage not imminent and drawdown continuing at a high rate, hydrogeologists are predicting dire consequences for the future groundwater supplies of the Chicago area.
Due to its extensive development, the Cambrian-Ordovician Aquifer system of northeastern Illinois is one of the more thoroughly studied confined aquifer systems in the United States. As early as 1919, with the work of Carl Anderson, the status of the aquifer was examined and its development summarized. Since that time, the various state surveys of Illinois and, to a lesser extent, the United States Geological Survey have conducted an active program of data collection for this aquifer system. Especially in the last two decades, since the landmark work of Suter et al. (1959), the Cambrian-Ordovician Aquifer of the Chicago area has received increasing amounts of attention. This overview of Suter et al. (1959) and the quantitative work of Walton (1960, 1962) in the early sixties, combined with the modelling work of Prickett and Lonnquist (1971) a decade later, and set within the context of the five year pumping and water level data summaries of Sasman et al. (1973, 1977), form an excellent basis from which an investigation into the behavior of this aquifer system can begin.

3.3 MODELLING INVESTIGATION

Close to a decade has passed since the modelling work of Prickett and Lonnquist (1971), so the northeastern section of Illinois was considered to be an excellent area
in which to test the capabilities of the automated package as well as to revise the earlier modelling work. Since the emphasis of this paper is on the Automated Hydrogeologic System, the complete modelling investigation will not be described. Only the first portions of the study in which the layered hydraulic conductivity distribution was examined will be discussed. Prior to initiating discussion of the application of the automated network the geologic and hydrologic framework of the area must be delineated.

3.31 Hydrogeology of Field Area

As shown in Figure 6, the Chicago area of northeastern Illinois lies on the southeastern flank of the Wisconsin Arch astride a smaller adjacent structure known as the Kankakee Arch. To the east and south the formations dip down into the Michigan and Illinois Basins respectively. Figure 7, a stratigraphic column of the area, reveals a cyclic alternation of sandstones, shales, and dolomites characteristic of transgressive-regressive sequences overlying Pre-Cambrian granites and topped by glacial deposits of Quaternary age.

The stratigraphic column of Figure 7 can be lumped into a water table aquifer – aquiclude – confined aquifer – aquiclude – confined aquifer – aquiclude sequence. This
FIGURE 6 - Bedrock geology map of the north-central U.S. Note that the boxed area approximately outlines the northeastern Illinois study area. (After Willman, p. 4)
FIGURE 7 - Stratigraphy and aquifer systems of northeastern Illinois. Note that this paper considers the Glacial Drift Aquifer and the Shallow Bedrock Aquifer as an interconnected system. (After Hughes et al., p. 3)
report will concentrate on the upper confined aquifer of the system, the Cambrian-Ordovician Aquifer. Before discussion of this aquifer can commence, the other water bearing units of the area should be briefly touched upon.

3.311 Adjoining Units

The Cambrian-Ordovician Aquifer is bounded both top and bottom by thick sequences of relatively impermeable shales: the Maquoketa Shale of the Ordovician and the upper portions of the Eau Claire Formation of Cambrian age respectively. Though both units are characterized by very low vertical hydraulic conductivities, significant amounts of water have undoubtedly passed through these units over their long geologic history.

The water table aquifer above the Maquoketa Shale consists of two rock types, each with vastly differing transmissive properties. Though the stratigraphic column of Figure 7 chooses to differentiate between a shallow dolomite and a glacial drift aquifer, this report will treat them as one interconnected unit. The lower portions of the aquifer consist of shallow sea dolomite of Silurian age. Due to the low permeability of the dolomite matrix, most water is transmitted along fractures and crevices which have been enlarged through dissolution. The upper
portions of the aquifer, made up of a variety of glacial deposits from Pleistocene times, are characterized by the great variation in hydraulic conductivity so often found in such deposits. When glacio-fluvial deposits directly overlie the dolomite, a fairly good hydraulic connection exists between the two units. In areas where impermeable glacial till material is immediately overlying the dolomite, head differences often develop. These differences, however, are generally of a local extent and thus, on a regional scale, the units are considered to behave as one aquifer.

Below the shales of the upper Eau Claire Formation lies the lower confined aquifer of the system, the Mt. Simon Aquifer. The Mt. Simon is made up of the lower, sandy portions of the Eau Claire Formation and the thick sequences of the Mt. Simon Sandstone. Though this aquifer is as much as 2000 feet thick in portions of the area, serious mineralization problems prevent much of it from being developed. The result is that only very limited data exist concerning the role of the Mt. Simon Aquifer in the subsurface hydrologic picture of northeastern Illinois.

3.312 Cambrian-Ordovician Aquifer

The Cambrian-Ordovician Aquifer is comprised of the
six geohydrologic units shown in Figure 7. "Available data indicates that on a regional basis, the entire sequence of strata, from the top of the Galena-Platteville to the top of the shale beds of the Eau Claire Formation, essentially behaves hydraulically as one aquifer." (Suter et al., 1959, p. 48) The data upon which the above statement was based were obtained after the aquifer had been pierced by hundreds of uncased wells, so their value for pre-development conditions is open to question. However, the early data that is available does indicate that treating the system as one interconnected aquifer is not an unreasonable approximation. Thus, for this predevelopment study, these geohydrologic units are considered to behave as one hydraulically connected unit.

The Cambrian-Ordovician Aquifer primarily consists of a series of alternating sandstone and dolomite units. Not surprisingly, the predominant flow mechanism in these units differs markedly. In the dolomites, flow occurs chiefly through the solution-enlarged fractures with little movement taking place through the relatively impermeable interfracture matrix. Flow in the sandstone units, on the other hand, occurs predominantly through the matrix of the rock according to the classic laws of porous media flow.
Due to the sparsity of pumping tests limited to one layer, little information exists concerning the transmissive properties of the individual units of the aquifer. The major source of information on hydraulic conductivities of the layers is the report of Walton and Csallany (1962) in which estimates are given based on specific capacity data. According to that work, the clean, friable sands of the Ironton-Galesville Formation generally have the highest hydraulic conductivities. On a local scale, however, the fracture-controlled permeability of the dolomites, notably the Trempealeau Formation, can be greater. The transmissive properties of these highly fractured zones contrast greatly with those of the unfractured matrix. Thus, it is of no great surprise that the tight, poorly creviced dolomites of the Galena-Platteville Formation appear to be the least permeable of the Cambrian-Ordovician units within the region of study.

3.313 Geologic Structure and Regional Interrelationships

A study of the geologic structure of the region reveals southeasterly dipping beds of relatively simple structure. The Sandwich Fault Zone of the southwestern portion of the area, shown in Figure 6, is the major large scale structure impinging on this simple pattern. Thought
to be of post-Silurian age, the Sandwich fault system is known to have experienced as much as 125 feet of vertical movement. A sparsity of wells in the fault area, however, makes evaluation of its effect on groundwater movement difficult.

Figure 8 illustrates the probable, pre-development interrelationships of the three aquifers in a schematic cross-section. Focusing on the Cambrian-Ordovician Aquifer, the main flow paths in the system are depicted. As shown, recharge occurs primarily in the west through zones of high vertical hydraulic conductivity. Flow to the southeast along the plane of the aquifer then takes place with water being discharged upward through the overlying Maquoketa Shale in the southeastern portions of the area. Along this flow path, substantial amounts of water are both gained and lost by movement through the confining beds of the Maquoketa Shale and the Eau Claire Formation. Though the majority of the recharge/discharge to the aquifer is thought to occur along the borders of the region, significant amounts undoubtedly percolate through the confining beds of the vast central portions of the area.

3.32 Investigation Objectives
FIGURE 8 - Schematic west-east cross-sectional view of aquifer interrelationships in northeastern Illinois. Note that for systems other than the Cambrian-Ordovician Aquifer only water movements into or out of the Cambrian-Ordovician Aquifer are shown.
In order to assess the behavior of the Cambrian-Ordovician Aquifer under dewatering conditions, a better knowledge of the layered hydraulic conductivity picture is necessary. Based on past estimates, dewatering the formations above the Ironton-Galesville would result in a 15% (Suter et al., 1959) or a 50% (Walton and Csallany, 1962) decrease in the specific capacity of wells fully penetrating the aquifer. Obviously, projections based on these two estimates could differ greatly. In hopes of better defining the distribution of hydraulic conductivities, a digital groundwater model set within the Automated Hydrogeologic System was applied to the area.

The digital model calculated the layered hydraulic conductivity distribution by treating the steady state, pre-development piezometric surface as a known and obtaining the conductivities through trial and error adjustment of parameters. Admittedly, this modelling investigation was a crude attempt to define the horizontal conductivity distribution in the vertical dimension. The focus of the study, however, was more to demonstrate the capabilities of the automated package than to exactly portray the situation found in northeastern Illinois, so the modelling effort was considered adequate.
3.33 Modelling Preliminaries

The particular digital groundwater model used in the study was the Modified Trescott Model discussed previously. A map of the pre-development piezometric surface, shown in Figure 9, primarily based on the work of Anderson (1919), was obtained from the 1959 report of Suter et al. Despite the uncertainty associated with this map, the author, based on his knowledge of the aquifer, considered it highly unlikely that the map values at any point varied by more than five percent from the actual pre-development piezometric surface. In order to remove further uncertainties, the investigation was restricted to the region in which the thicknesses of the aquifer layers and the overlying Maquoketa Shale were well known. Also, areas of hydrologic uncertainty, such as beneath Lake Michigan, were excluded from the investigation.

Figure 10 shows the six county area of northeastern Illinois involved in this study. The solid line delineates the area which was actually modelled, the fluctuations of the boundary on the western edge of the map being due to erosion in the Maquoketa Shale. The grid for this study was a 48 column by 33 row network of constant spacing. The distance between each line of the grid was approximately two miles, thus making the square cells surrounding each node, assumed by the model to have constant hydrogeologic
FIGURE 9 - Pre-development piezometric surface of Cambrian-Ordovician Aquifer; Estimated historical values. Map has not undergone automated processing. (After Suter et al., p. 52)
FIGURE 10 - Map outline of northeastern Illinois study area. Dashed lines indicate county boundaries while solid line bounds modelled area.
properties, four square miles in area. Given the available data, grid cells of this size seemed reasonable for a pre-development, steady state investigation.

The modelled area outlined in Figure 10 is bounded on three sides by constant head boundaries and on one side by a boundary of constant flow. Not one of these boundaries was strictly based on geologic or hydrologic considerations, instead they were controlled by data limitations. Except for the Maquoketa Shale in the west, these boundaries generally follow geographical and political divisions of the region. In order to pose a problem which would be sensitive to changes in hydraulic conductivity, the majority of the southern edge was chosen to be a constant flow boundary. The values for the constant flow restrictions were calculated using the steady state hydraulic gradient of Figure 9 and layered conductivities from Walton and Csallany (1962). Figure 9 also supplied the hydraulic potentials for the three constant head boundaries. Specific values for the boundary nodes can be found in the input matrices of Appendix C. Note that the western boundary follows the eastern edge of the Maquoketa outcrop area. To the west of this line, the Maquoketa Shale is the topmost bedrock unit. Since relatively little data exist concerning the thickness of the shale in this region, the boundary was drawn at the
edge of this area in order to utilize the abundant data to the east without introducing further uncertainties.

In order to fulfill input requirements for the groundwater model, information was needed detailing formation thicknesses, their hydraulic conductivities, and the pre-development steady state water levels. Storage coefficients do not play a role in steady state modelling so they were not considered in this investigation. The horizontal hydraulic conductivities of the aquifer layers, the vertical conductivities of the Maquoketa Shale, as well as the pre-development water levels of the unconfined aquifer were obtained from the literature and will be discussed later. Information concerning formation thicknesses and the pre-development water levels of the Cambrian-Ordovician Aquifer was in the form of contour and discrete point maps of differing scale and areal coverage. The task of changing these data into a form amenable to digital processing appeared quite formidable. At this point, the Automated Hydrogeologic System was introduced into the investigation in order to ease the pain of transforming the data into a form suitable for a digital groundwater model.

3.34 Use of Automated Network in Modelling Investigation
3.341 Computer Entry

The first step in a modelling investigation using the automated package is to transform the gathered data into a machine readable form. In northeastern Illinois all necessary data detailing formation thicknesses and pre-development water levels of the Cambrian-Ordovician Aquifer were available in a mapped form, either as contour or discrete point maps. Thus, the digitizer could be utilized in the data entry procedure. The Super Hydra and Super Buth programs were used to digitize contour and discrete point maps respectively. A total of seven maps were digitized during the study; six geologic formation maps and Figure 9, the map of the pre-development piezometric surface of the Cambrian-Ordovician Aquifer. Figure 11 is an example of a geologic map which was digitized using the Super Hydra program. For this map of the Maquoketa Shale, in addition to the thickness contour lines, the western edge of the overlying unit was also digitized. Since this had been chosen as the western boundary of the area, the digitized trace was used to fit the boundary onto the rectangular grid. Actually to digitize the trace of the western edge, a program called Summa, similar to Super Hydra and Super Buth, was used to record the X and Y coordinates of each point.
FIGURE 11 - Formation thickness map for Maquoketa Shale. This map is used in the sample SURFACE II runs of Appendix B. (After Buschbach, pl. 8)
3. Parameter Estimation

Once all the information had been recorded in a digital form, the spatial analysis package was used to obtain estimates of the needed parameters at each grid node. As discussed earlier, the specific spatial analysis package utilized was that developed by the Kansas Geological Survey, the SURFACE II system. In addition to estimation of parameters at grid nodes, the SURFACE II package in several cases used its nodal manipulation routines to obtain needed thicknesses by subtracting bounding formation surfaces. A sample listing from a run of the SURFACE II system in which nodal values for the thickness of the Maquoketa Shale were estimated can be found in Appendix B. Note that selected values obtained through the automated procedure were altered during the user review and modification process. These apparent errors were thought to have been a product of several regions of low data density. The new values were computed from surrounding nodes assuming a uniform slope.

The distance weighted averaging scheme was used for estimation of parameters at grid nodes in the Illinois study. This technique was chosen primarily for its simplicity and cost effectiveness. Further study showed that the trend surfaces method handled data density problems more effectively than distance weighted averaging.
However, this increased effectiveness in handling of data density problems was counterbalanced by a decrease in accounting of local trends. The kriging method was avoided throughout the study due to warnings concerning errors in its algorithms. (Gorelick, 1981, personal communication)

3.343 User Review and Modification

The user review and modification procedure was accomplished by comparison of maps and listings of the automatically estimated parameters with the original maps which had been used in the digitizing process. Except for regions of low data density, the comparison was satisfactory. In these areas, due to a sparsity of data control points, the estimation procedure led to results of questionable validity. Such estimates were subsequently modified based on projections of uniform slope from areas of higher data density.

3.344 Assigning Values to Unmapped Parameters

The above discussion has focused on the handling of mapped data amenable to processing using the digitizer and spatial analysis package. However, the horizontal conductivities of the aquifer layers, the vertical conductivities of the Maquoketa Shale, and the
pre-development water levels of the unconfined aquifer were not subject to this processing and thus must be treated separately.

The first set of layered hydraulic conductivities was obtained from the 1962 report of Walton and Csallany. These values were later modified during inversions based on further information from Walton and Csallany (1962), on knowledge of changes in the geologic characteristics of the layers, and on the differences between the model calculations and the estimated historical water levels.

In this study, leakage was considered to be occurring only through the Maquoketa Shale. Flow through the shales of the upper Eau Claire was ignored due to a sparsity of data and the inability of the model to handle leakage from more than one unit. The vertical hydraulic conductivities of the Maquoketa Shale were based on the flow net study of Walton (1960). The water levels of the overlying unconfined aquifer came from a variety of sources including works by Anderson (1919), Walton (1960), and Zeisel et al. (1962). The model input matrices for all the discussed parameters can be found in Appendix C.

3.345 Model Operation and Verification
With values having been assigned to all needed parameters, the automated package moved from the data processing phase to that of model operation. However, before the estimated values could be utilized by the groundwater model they had to be transformed into the requisite format. As was discussed in Chapter One, this procedure was performed by a simple program, called Condor, associated with the Modified Trescott Model. Once the inputted information had thus been transformed, it could be utilized by the model and the actual simulation performed.

The model, using the estimated parameter values, computed a piezometric surface for the Cambrian-Ordovician Aquifer under pre-development, steady state conditions. In order to test the validity of the results, this calculated surface was compared to the historical water levels of Figure 9 which had also undergone automated processing. This comparison not only took the form of visual review of contour maps of the two piezometric surfaces, but in addition, a contour map of the differences between the surfaces was automatically produced. Also, to enable manual node by node comparison of the results, listings of the nodal values for both the calculated and historical cases were obtained.
3.3451 Inversing Loop

Since the calculated and historical water levels differed significantly, the inversing loop was entered in order to reduce this disparity. The boundary conditions, the formation thicknesses, the vertical conductivity of the confining unit, and the height of the water table were all considered known to within an acceptable error, so the horizontal hydraulic conductivities of the aquifer layers were chosen as the primary parameters for adjustment during inversing. These values were adjusted considering the geologic and hydrologic information mentioned earlier. The new estimates of these hydraulic parameters were then entered into the input data set and the model rerun. This procedure was repeated ten times before a satisfactory piezometric surface was obtained. This calculated surface reasonably approximated the estimated historical values and was defensible in a hydrologic and geologic sense. The maximum difference between the calculated and historical surfaces after the final run was 9.4 feet with the average being much lower. Figure 12 is a map of the final calculated piezometric surface with Figure 13 being a map of the corresponding historical water levels. The layered horizontal hydraulic conductivity distribution of the final run is given by the model input matrices found in Appendix C.
FIGURE 12 - Pre-development piezometric surface of Cambrian-Ordovician Aquifer; Calculated values.
Contour map is product of SURFACE II graphics routines.
At this point in most investigations, this calibrated model would be used both to make conclusions about system behavior and to support development plans. In this case, however, the paucity of data and the restrictive boundary conditions made the model of limited usefulness since the main goal of this modeling exercise was to test the capabilities of the automated network, rather than to simulate the flow processes. The useability of the calibrated model was not a prime concern.

4 DISCUSSION

Considering all the procedures which were automated during the study in northeastern Illinois, the estimated time saved through use of the Automated Hydrogeologic System was on the order of weeks! Seven maps were digitized and nodal values automatically estimated in less than six hours, a process which would have taken over two weeks if done by traditional means. The system graphics produced types automatically with only a minor effort by the author. Given the significant amount of time saved without sacrificing

FIGURE 13 - Pre-development piezometric surface of Cambrian-Ordovician Aquifer; Estimated historical values. Map has undergone automated processing. (After Suter et al., p. 52)
3.35 Use of Model Results

At this point in most investigations, this calibrated model would be used both to make conclusions about system behavior and to evaluate proposed aquifer development plans. In this case, however, the sparsity of data and the very restrictive boundary conditions made the model of limited usefulness. Since the main goal of this modelling exercise was to test the capabilities of the automated network, rather than to exactly simulate the flow processes, the useability of the calibrated model was not a prime concern.

3.4 DISCUSSION

Considering all the procedures which were automated during the study in northeastern Illinois, the estimated time saved through use of the Automated Hydrogeologic System was on the order of weeks! Seven maps were digitized and nodal values automatically estimated in less than six hours, a process which would have taken over two weeks if done by traditional means. The system graphics produced maps of all types automatically with only a minimum effort exerted by the author. Given the significant amount of time saved without sacrificing modelling accuracy, this application of the Automated Hydrogeologic System was considered quite successful.
However, this was only an initial investigation of its capabilities. Further work must be done before its true usefulness in hydrogeologic studies can be evaluated.
CHAPTER FOUR

CONCLUSION

4.1 SUMMARY

The foremost goal of this research project was the development of a system to automate many of the relatively mindless tasks in hydrogeologic modelling investigations. Coupling with a digital groundwater model was desired so that an integrated package could be produced. An additional goal of the project was the evaluation of the capabilities of the automated network through an actual modelling investigation. The need to integrate a digital groundwater model into the automated package, combined with the specific problems faced in the area to be modelled, resulted in a third goal for the project; that being the development of a groundwater model which could be utilized within the framework of the automated package as well as meeting the requirements of the area under study.

The development of the Automated Hydrogeologic System was discussed in Chapter One. The eight steps of the traditional hydrogeologic modelling investigation were first presented and then the automated package was introduced. The main emphasis of the subsequent discussion
revolved around the great time savings the automated network allows in the contour data, estimate parameters at grid nodes, computer entry steps of the traditional modelling investigation. The digitizer and the spatial analysis package were singled out as the factors primarily responsible for this savings. Specific programs for the digitizer were discussed along with details of a spatial analysis package created by the Kansas Geological Survey. Despite the emphasis on automation, the importance of the user review and modification step was stressed. This step enables the user to interject his subjective feelings about the studied area as well as correct errors arising from the application of the automated network in areas of low data density. The final portions of the discussion of the automated package concerned its graphics capabilities, the incorporation of inversing procedures into the network, and the all-important system limitations.

Chapter Two dealt with the digital groundwater model incorporated in the network for the northeastern Illinois investigation. A brief introduction to digital groundwater models was presented before delving into the details of the particular model utilized in this study. The model used was a version of the United States Geological Survey groundwater model (Trescott et al., 1976) which was extensively modified to meet the requirements of the area
chosen for study. A hypothetical island aquifer was used to validate this modified model in the last portion of the chapter to ensure that no errors were produced as a result of the modifications.

The third chapter concerned the actual application of the automated network to an aquifer system in northeastern Illinois. After a brief overview of the area, the pre-development, steady state scenario was outlined and the modelling process was described while stressing the role of the automated network in the procedure. The results of this application showed that literally weeks could be saved by utilizing the Automated Hydrogeologic System in modelling investigations.

4.2 BENEFITS AND LIMITATIONS

The future of such an automated system in hydrogeologic modelling is bright. Especially in the area of hydrogeologic consulting, these systems should become quite common in the near future. Admittedly, the majority of the work described in this paper was performed on a computer of a mainframe scale not always accessible to the consulting hydrogeologist. However, the continuing trend toward computer minaturization will shortly result in such packages becoming suitable for smaller machines. The
author is currently beginning a project with the goal of installing a modified version of the Automated Hydrogeologic System on a microcomputer. The successful completion of this project would result in many consulting firms, previously unable to participate in modelling investigations due to computer limitations, taking a much more active role.

Before getting too caught up in rosy visions of the future, the limitations of the current system should be emphasized. As in almost all aspects of hydrogeology, the data availability is the great limiting factor. Whether the task is estimating parameter values at grid nodes or actually modelling a groundwater basin, data deficiencies will seriously influence the accuracy of the calculations. Though both tasks produce results of apparent high accuracy, these results are only as good as the data input into the problem. Areas of low data density as well as errors within the data will produce results of dubious quality. The reader should recall the more specific limitations of the spatial analysis package which must also be kept in mind when utilizing the automated network in modelling investigations.

Despite these limitations, automated systems such as that developed in this report will become commonplace in
hydrogeologic modelling. For the advantages of the automated network do far outweigh any of its limitations. Through the use of such a system, the hydrogeologist is able to free himself from the heavy data processing demands of the traditional modelling investigation and concentrate on the real problem of understanding aquifer behavior. However, it is crucially important that the Automated Hydrogeologic System not be considered totally automatic. User interaction and modification must be stressed and must go hand in hand with the automated processing so that a useful tool is produced rather than a mindless black box.
REFERENCES


Sampson, R. J., [1978], SURFACE II graphics system (2d ed.): Kansas Geological Survey Series on Spatial Analysis No. 1, 240 p.


APPENDIX A

COMPUTER PROGRAMS OF AUTOMATED HYDROGEOLOGIC SYSTEM

<table>
<thead>
<tr>
<th>Program</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super Hydra Program</td>
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<tr>
<td>Super Buth Program</td>
<td>95</td>
</tr>
<tr>
<td>Condor Program</td>
<td>100</td>
</tr>
<tr>
<td>Giveme Program</td>
<td>101</td>
</tr>
<tr>
<td>Modified Trescott Program</td>
<td>A1</td>
</tr>
</tbody>
</table>

A1 is in back pocket.
SUPHYDRA PROGRAM

PROGRAM FOR DIGITIZING CONTOUR LINES

MODIFIED BY JAMES BUTLER - APRIL, 1981

DIMENSION LEFTLN(3), ALFTLN(3), LFTSCL(3), B(2, 2), C(2), D(10, 4)
INTEGER XYCord(3), RGTSCLO
BYTE NAME(11)

OPEN output file
WRITE(5, 111)
READ(5, 112) (NAME(I), I=1, 10)
OPEN(UNIT=3, NAME=NAME, TYPE='UNKNOWN', ACCESS='APPEND', ERR=110)

INTIALIZE VARIABLES FOR SUPER HYDRA OPTION

N = 0
XMAX = 0.0
XMIN = 0.0
YMAX = 0.0
YMIN = 0.0
ZMAX = 0.0
ZMIN = 0.0

DIGITIZE LEFT MAP EDGE AND CALCULATE ANGLE OF ROTATION

TYPE 660
FORMAT('LINEAR REGRESSION TO CALCULATE ANGLE OF ROTATION')
TYPE 661
FORMAT('REGRESSION USES 10 POINTS ON LEFT EDGE OF MAP'
1'PLEASE BEGIN DIGITIZING AT MAP BOTTOM')
DO 662 I=1, 2
C(I) = 0.0
DO 662 J=1, 2
B(I, J) = 0.0
CONTINUE

CALL SUMMA(IFLAG, LEFTLN)
ALFTLN(2) = FLOAT(LEFTLN(2))
ALFTLN(3) = FLOAT(LEFTLN(3))
B(1, 1) = B(1, 1) + 1.0
B(1, 2) = B(1, 2) + ALFTLN(3)
B(2, 2) = B(2, 2) + (ALFTLN(3) * ALFTLN(3))
C(1) = C(1) + ALFTLN(2)
C(2) = C(2) + (ALFTLN(2) * ALFTLN(3))
D(1, 1) = ALFTLN(3)
D(1, 2) = ALFTLN(2)
DO 664 I=2, 10
CONTINUE

CALL DGT(IFLAG, LEFTLN)
ALFTLN(2) = FLOAT(LEFTLN(2))
ALFTLN(3) = FLOAT(LEFTLN(3))
B(1, 1) = B(1, 1) + 1.0
B(1, 2) = B(1, 2) + ALFTLN(3)
B(2, 2) = B(2, 2) + (ALFTLN(3) * ALFTLN(3))
C(1) = C(1) + ALFTLN(2)
C(2) = C(2) + (ALFTLN(2) * ALFTLN(3))
D(I, 1) = ALFTLN(3)
D(I, 2) = ALFTLN(2)

CONTINUE
B(2, 1) = B(1, 2)
COEF2 = (C(2) - ((B(1, 2)*C(1))/B(1, 1)))/(B(2, 2) - (B(1, 2)**2.0)
1/B(1, 1))
COEF1 = (C(1) - COEF2 * B(1, 2))/B(1, 1)
SY = 0.0
SY2 = 0.0
SYC = 0.0
SYC2 = 0.0
DO 665 I=1,10
D(I, 3) = COEF1 + (COEF2 * D(I, 1))
D(I, 4) = D(I, 2) - D(I, 3)
SY = SY + D(I, 2)
SY2 = SY2 + (D(I, 2) * D(I, 2))
SYC = SYC + D(I, 3)
SYC2 = SYC2 + (D(I, 3) * D(I, 3))
CONTINUE
SST = SY2 - (SY * SY)/10.0
SSR = SYC2 - (SYC * SYC)/10.0
SSD = SST - SSR
R2 = SSR/SST
R = SQRT(R2)
XNEW1 = COEF1 + COEF2
XNEW2 = COEF1 + (COEF2 * 500.0)
XDIST = XNEW2 - XNEW1
YDIST = 500.0 - 1.0
RAD = -ATAN(XDIST/YDIST)
DEG = (RAD * 180.0)/3.141593
WRITE(5, 5) DEG
WRITE(3, 5) DEG
5 FORMAT(' ANGLE OF ROTATION = ',F9.5, ' DEGREES')
WRITE(5, 666) SST
WRITE(3, 666) SST
666 FORMAT(' TOTAL SUM OF SQUARES = ',F15.4)
WRITE(5, 667) SSR
WRITE(3, 667) SSR
667 FORMAT(' SUMS OF SQUARES DUE TO REGRESSION = ',F15.4)
WRITE(5, 668) SSD
WRITE(3, 668) SSD
668 FORMAT(' SUMS OF SQUARES DUE TO DEVIATION = ',F15.4)
WRITE(5, 669) R2
WRITE(3, 669) R2
669 FORMAT(' GOODNESS OF FIT = ',F15.6)
WRITE(5, 670) R
WRITE(3, 670) R
670 FORMAT(' CORRELATION COEFFICIENT = ',F15.6)
C -- -- -- DIGITIZE LEFT BOTTOM CORNER OF MAP FOR TRANSLATION -- -- --
C --
TYPE 671
671 FORMAT(' PLEASE DIGITIZE LOWER LEFT HAND CORNER OF MAP'/ ' THIS 1 WILL BE USED AS THE NEW ORIGIN')
CALL DGT(IFLAG,LEFTLN)
AORG = FLOAT(LEFTLN(2))
BORG = FLOAT(LEFTLN(3))
WRITE(5, 672) AORG,BORG
WRITE(3, 672) AORG,BORG
DO 100 I = 1, 100
  WRITE(5, 17)
  FORMAT(' PLEASE DIGITIZE X AND Y COORDINATES OF POINT ON CONTOUR LINE' )
  CALL DGT( IFLAG, XYCORD)
  X = FLOAT(XYCORD(2))
  Y = FLOAT(XYCORD(3))
  Z = FLOAT(KELEV)
  CALL DGT( IFLAG, LFTSCL)
  X = FLOAT(RGTSCL(2)) - LFTSCL(2)
  Y = FLOAT(RGTSCL(3)) - LFTSCL(3)
  ADIST = SQRT((FLOAT(RGTSCL(2)) - LFTSCL(2))**2.0) + (FLOAT(RGTSCL(3)) - LFTSCL(3))**2.0)
  AMILE = ADIST/SCMAP
  WRITE(3, 10) AMILE
  WRITE(5, 10) AMILE
  CALL DGT( IFLAG, RGTSC)
  WRITE(S, 20) A
  WRITE(5, 20) A
  ACCEPT *, KELEV
  TYPE 567
  CALL DGT( IFLAG, LFTSCL)
  CALL DGT( IFLAG, RGTSC)
  X = (((XI - AORG) * COS(RAD)) + ((Y1 - BORG) * SIN(RAD))
  Y = (((XI - AORG) * SIN(RAD)) + ((Y1 - BORG) * COS(RAD))
  Z = kelev
  k = k + 1
  GO TO 100
  ELIF A. NE. 1.0 GO TO 700
  ELSE CONTINUE
C Write X, Y and elevation to the disk file.

`WRITE(3,107) X, Y, Z`

`FORMAT(3F8.2)`

`N = N + 1`

`IF(N.LE.1) XMIN = X`

`IF(N.LE.1) YMIN = Y`

`IF(N.LE.1) ZMIN = Z`

`IF(X.GT.XMAX) XMAX = X`

`IF(X.LT.XMIN) XMIN = X`

`IF(Y.GT.YMAX) YMAX = Y`

`IF(Y.LT.YMIN) YMIN = Y`

`IF(Z.GT.ZMAX) ZMAX = Z`

`IF(Z.LT.ZMIN) ZMIN = Z`

`IF(IFLAG EQ. 2) GO TO 444`

`IF(IFLAG EQ. 1) GO TO 155`

`CONTINUE`

`WRITE(5,160) N, XMAX, XMIN, YMAX, YMIN, ZMAX, ZMIN`

`WRITE(3,160) N, XMAX, XMIN, YMAX, YMIN, ZMAX, ZMIN`

`FORMAT(19,6F8.2)`

C End of data-normal exit

`CLOSE(UNIT=3)`

`STOP `Normal end of data.``

C STOP 'Failed to open the output file.'

END

C -- -- SUBROUTINE USED TO ACTUALLY READ IN DATA IN DIGITIZED FORM

C

SUBROUTINE SUMMA(Status, STBUF)

INTEGER RLB, WLB, STATUS, PARAM(6), IOSB(2), STBUF(3), TTY

BYTE BELL

DATA RLB, WLB, BELL, TTY/*1000, "400, "007, 5/`

C C ASSIGN A LOGICAL UNIT NUMBER TO THE SUMMAGRAPHICS TABLET

CALL ASNLUN(2, 'ST', 0, IDS)

IF(IDS.NE. 1) WRITE(TTY, 100) IDS

`FORMAT(1H, 'Tablet ASNLUN error. Status: ', 15)`

C

C -- -- NORMAL ENTRY POINT FOR DIGITIZING -- --

ENTRY DGT(Status, STBUF)

C

C Prompt user with tty bell (cntrl-g)

`WRITE(TTY, 101)`

`FORMAT(1H, 'Ready to accept a data point when the bell sounds. ')

C Sound the bell

`CALL GETADR(PARAM(1), BELL)`

PARAM(2)=1

PARAM(6)="40`

`CALL WTQIO(WLB, TTY, 1, , IOSB, PARAM, IDS)`

C

C Issue read to tablet device, and check for error status

`CALL GETADR(PARAM(1), STBUF(1))`

PARAM(2)=6

`CALL WTQIO(RLB, 2, 1, , IOSB, PARAM, IDS)`

`IF(IOSB(1).EQ.1) GO TO 106`

C

C Exit on all device errors except power off
WRITE(TTY, 104) IDS, IOSB
104 FORMAT(1H, 'Tablet device error. Directive and I/O status: ', 1 ', ', 207)
   IF(IOSB(1).NE."375)GO TO 109
WRITE(TTY, 105)
105 FORMAT( 'Turn tablet power on and hit carriage return. ')
READ(TTY, 103)IGO
103 FORMAT(1A1)
GO TO 102
C
C Successful read from tablet-check for flags
106 STATUS=0
   IF(IAND(STBUF(1), "100000).EQ."100000)STBUF(2)=-STBUF(2)
   IF(IAND(STBUF(1), "40000).EQ."40000)STBUF(3)=-STBUF(3)
   IF(IAND(STBUF(1), "40000).EQ."40000)STBUF(3)=-STBUF(3)
   IF(IAND(STBUF(1), "20000).EQ."20000)STATUS=2
   IF(IAND(STBUF(1), "10000).EQ."10000)STATUS=3
RETURN
C
C Error exits
109 CLOSE(UNIT=3)
STOP 'UNKNOWN DEVICE PROBLEM.'
END
C - - - - - - - - - - SUPER BUTH PROGRAM - - - - - - - - - -
C - - - PROGRAM TO DIGITIZE LOCATION AND MAGNITUDE OF DISCRETE POINTS -
C - - - DEVELOPED BY JAMES BUTLER AND RICHARD ROTH - APRIL, 1981

C - - - - - - - - - - BEGIN PROGRAM - - - - - - - - - -
DIMENSION MINXY(3), MAXXY(3), LEFTLN(3), ALFTLN(3), LFTSCL(3), B(2, 2)
DIMENSION C(2), D(10, 4)
INTEGER XYCORD(3), VAL(3), RGTSCL(3)
BYTE NAME(11)

C Open output file
WRITE(5, 111)
111 FORMAT( 'Output file name?')
READ(5, 112) (NAME(I), I=1, 10)
112 FORMAT(IOAI>)
NAME(11)=0
OPEN(UNIT=3, NAME=NAME, TYPE='UNKNOWN', ACCESS='APPEND', ERR=110)

C - - - INITIALIZE VARIABLES FOR SUPER BUTH OPTION - - -
N = 0
XMAX = 0.0
XMIN = 0.0
YMAX = 0.0
YMIN = 0.0
ZMAX = 0.0
ZMIN = 0.0

C - - DIGITIZE LEFT MAP EDGE AND CALCULATE ANGLE OF ROTATION - - -
C USING LINEAR REGRESSION

C - - - ANGLE WILL BE GIVEN IN DEGREES - - - - - - - - - -
TYPE 660
660 FORMAT('LINEAR REGRESSION TO CALCULATE ANGLE OF ROTATION')
TYPE 661
661 FORMAT('REGRESSION USES 10 POINTS ON LEFT EDGE OF MAP')
1 'PLEASE BEGIN DIGITIZING AT MAP BOTTOM'/
DO 662 I=1, 2
C(I) = 0.0
DO 662 J=1, 2
B(I, J) = 0.0
662 CONTINUE

1 FORMAT('PLEASE DIGITIZE POINT ON LEFT EDGE OF MAP')
CALL SUMMA(IFLAG, LEFTLN)
ALFTLN(2) = FLOAT(LEFTLN(2))
ALFTLN(3) = FLOAT(LEFTLN(3))
B(1, 1) = B(1, 1) + 1.0
B(1, 2) = B(1, 2) + ALFTLN(3)
B(2, 2) = B(2, 2) + (ALFTLN(3) * ALFTLN(3))
C(1) = C(1) + ALFTLN(2)
C(2) = C(2) + (ALFTLN(2) * ALFTLN(3))
D(1, 1) = ALFTLN(3)
D(1, 2) = ALFTLN(2)
DO 664 I=2, 10

1 FORMAT( 'PLEASE DIGITIZE POINT ON LEFT EDGE OF MAP')
CALL DGT(IFLAG, LEFTLN)
ALFTLN(2) = FLOAT(LEFTLN(2))
ALFTLN(3) = FLOAT(LEFTLN(3))
B(1, 1) = B(1, 1) + 1.0
B(1, 2) = B(1, 2) + ALFTLN(3)
B(2, 2) = B(2, 2) + (ALFTLN(3) * ALFTLN(3))
C(1) = C(1) + ALFTLN(2)

1
C(2) = C(2) + (ALFTLN(2) * ALFTLN(3))
D(I, 1) = ALFTLN(3)
D(I, 2) = ALFTLN(2)

CONTINUE
B(2, 1) = B(1, 2)
COEF2 = (C(2) - ((B(1, 2)*C(1))/B(1, 1)))/(B(2, 2)-(B(1, 2)**2.0))
1/B(1, 1))
COEF1 = (C(1) - COEF2 * B(1, 2))/B(1, 1)
SY = 0.0
SY2 = 0.0
SYC = 0.0
SYC2 = 0.0
DO 665 I=1,10
D(I, 3) = COEF1 + (COEF2 * D(I, 1))
D(I, 4) = D(I, 2) - D(I, 3)
SY = SY + D(I, 2)
SY2 = SY2 + (D(I, 2) * D(I, 2))
SYC = SYC + D(I, 3)
SYC2 = SYC2 + (D(I, 3) * D(I, 3))
CONTINUE

SST = SY2 - (SY * SY)/10.0
SSR = SYC2 - (SYC * SYC)/10.0
SSD = SST - SSR
R2 = SSR/SST
R = SQRT(R2)
XNEW1 = COEF1 + COEF2
XNEW2 = COEF1 + (COEF2 * 500.0)
XDIST = XNEW2 - XNEW1
YDIST = 500.0 - 1.0
RAD = -ATAN(XDIST/YDIST)
DEG = (RAD * 180.0)/3.141593
WRITE(5, 5) DEG
WRITE(3, 5) DEG
5 FORMAT( 'ANGLE OF ROTATION = ',F9.5,' DEGREES')
WRITE(5, 666) SST
WRITE(3, 666) SST
666 FORMAT( 'TOTAL SUM OF SQUARES = ',F15.4)
WRITE(5, 667) SSR
WRITE(3, 667) SSR
667 FORMAT( 'SUMS OF SQUARES DUE TO REGRESSION = ',F15.4)
WRITE(5, 668) SSD
WRITE(3, 668) SSD
668 FORMAT( 'SUMS OF SQUARES DUE TO DEVIATION = ',F15.4)
WRITE(5, 669) R2
WRITE(3, 669) R2
669 FORMAT( 'GOODNESS OF FIT = ',F15.6)
WRITE(5, 670) R
WRITE(3, 670) R
670 FORMAT( 'CORRELATION COEFFICIENT = ',F15.6)
C = -- -- DIGITIZE LEFT BOTTOM CORNER OF MAP FOR TRANSLATION -- -- --
C TYPE 671
671 FORMAT( 'PLEASE DIGITIZE LOWER LEFT HAND CORNER OF MAP'/ 'THIS
1 WILL BE USED AS THE NEW ORGIN')
CALL DGT(IFLAG,LEFTLN)
AORG = FLOAT(LEFTLN(2))
BORG = FLOAT(LEFTLN(3))
WRITE(5, 672) AORG, BORG
WRITE(3, 672) AORG, BORG
672 FORMAT(' NEW X ORIGIN POINT = ', F9.2, ' NEW Y ORIGIN POINT = ', F9.2) C - - - DIGITIZE EDGES OF SCALE BAR AND CALCULATE NUMBER - - - C OF DIGITIZED UNITS PER MILE ON MAP
TYPE 6
FORMAT(' PLEASE TYPE IN DISTANCE IN MILES REPRESENTED BY SCALE BAR') 1AR = (F8.2)
READ(5, 7) SCMAP
7 FORMAT(F8.2)
TYPE 8
FORMAT(' PLEASE DIGITIZE UPPER LEFT CORNER OF SCALE BAR')
CALL DGT(IFLAG, LFTSCL)
TYPE 9
FORMAT(' PLEASE DIGITIZE UPPER RIGHT CORNER OF SCALE BAR')
CALL DGT(IFLAG, RTGSCL)
C - - - CALCULATE DISTANCE BETWEEN DIGITIZED ENDPOINTS USING - - -
PYTHAGOREAN THEOREM
ADIST = SQRT((FLOAT(RTGSCL(2) - LFTSCL(2))**2.0) + (FLOAT(RTGSCL(3) - LFTSCL(3))**2.0))
C - - - CALCULATE UNITS PER MILE ON MAP - - - AMILE = ADIST/SCMAP
WRITE(3, 10) AMILE
WRITE(5, 10) AMILE
10 FORMAT(' UNITS PER MILE = ', F9.3)
C
C - - - READ MIN. AND MAX. VALUES OF VERTICAL SCALE - - - TYPE 11
11 FORMAT(' PLEASE TYPE IN MIN. AND MAX. VALUES OF VERTICAL SCALE - - - 1 (2F8.2)')
READ(5, 12) SMIN, SMAX
12 FORMAT (2F8.2)
C - - - COMPUTE ACTUAL DISTANCE COVERED ON SCALE - - - DIST = SMAX - SMIN
C - - - READ DIGITIZED VALUES OF MIN. AND MAX. VALUES OF SCALE - - - TYPE 13
13 FORMAT(' PLEASE READ IN DIGITIZED VALUE OF MIN. POINT ON SCALE')
CALL DGT(IFLAG, MINXY)
TYPE 14
14 FORMAT(' PLEASE READ IN DIGITIZED VALUE OF MAX. POINT ON SCALE')
CALL DGT(IFLAG, MAXXY)
C - - - CALCULATE DISTANCE BETWEEN DIGITIZED END POINTS USING
PYTHAGOREAN THEOREM
ENDIST = SQRT((FLOAT(MAXXY(2) - MINXY(2))**2.0) + (FLOAT(MAXXY(3) - MINXY(3))**2.0))
C - - - CHECK IF MULTIPLICATION BY MAP ROTATION IS DESTIRED - - -
1 TO BE MULTIPLIED/' BY ANGLE OF MAP ROTATION?')
TYPE 675
675 FORMAT(' YES - TYPE 1.0, NO - TYPE 0.0')
READ(5, 677) A
677 FORMAT(F8.2)
C - - - DO LOOP TO READ IN DIGITIZED COORDINATES OF MAP AND SCALE,
NORMALIZE SCALE COORDINATES, AND STORE THEM IN A FILE
TYPE 15
15 FORMAT(' REMEMBER TO PUNCH 1 ON LAST DIGITIZED POINT')
DO 50 I=1, 1000
50 TYPE 16
16 FORMAT('PLEASE READ IN X AND Y COORDINATES OF MAP POINT')
   CALL DGT(IFLAG, XYCORD)
   TYPE 17
17 FORMAT('PLEASE READ IN X AND Y COORDINATES OF SCALE POINT')
   CALL DGT(IFLAG, VAL)
   C --- --- SCALE VAL
   VALDIS = SGRT((FLOAT(VAL(2)) - MINXY(2))**2.0) + (FLOAT(VAL(3))
   1- MINXY(3))**2.0)
   VALS = (VALDIS/ENDIST) * DIST
   VALSCL = SMIN + VALS
   Z = VALSCL
   C --- --- WRITE DATA ONTO DATA FILE --- ---
   X = FLOAT(XYCORD(2))
   Y = FLOAT(XYCORD(3))
   C --- --- CORRECT X AND Y VALUES FOR MAP ROTATION --- ---
   IF(A. NE. 1.0) GO TO 700
   X1 = X
   Y1 = Y
   X = ((X1 - AORG) * COS(RAD)) + ((Y1 - BORG) * SIN(RAD))
   Y = (-(X1 - AORG) * SIN(RAD)) + ((Y1 - BORG) * COS(RAD))
   C Write X, Y and Z to the disk file.
   700 WRITE(3,20) X, Y, Z
   20 FORMAT(3FB.2)
   N = N + 1
   IF(N.LE.1) XMIN = X
   IF(N.LE.1) YMIN = Y
   IF(N.LE.1) ZMIN = Z
   IF(X.GT. XMAX) XMAX = X
   IF(X.LT. XMIN) XMIN = X
   IF(Y.GT. YMAX) YMAX = Y
   IF(Y.LT. YMIN) YMIN = Y
   IF(Z.GT. ZMAX) ZMAX = Z
   IF(Z.LT. ZMIN) ZMIN = Z
   IF(IFLAG.EQ.1) GO TO 51
   CONTINUE
   50 CONTINUE
   51 CONTINUE
   53 CONTINUE
   108 CLOSE(UNIT=3)
   109 STOP 'Normal end of data.'
   110 STOP 'Failed to open the output file.'
   END
   C --- --- SUBROUTINE USED TO ACTUALLY READ IN DATA IN DIGITIZED
   FORM
   SUBROUTINE SUMMA(STATUS, STBUF)
   INTEGER RLB, WLB, STATUS, PARAM(6), IOSB(2), STBUF(3), TTY
   BYTE BELL
   DATA RLB, WLB, BELL, TTY/"1000", "400", "007", 5/
   C
   C ASSIGN A LOGICAL UNIT NUMBER TO THE SUMMAGRAPHICS TABLET
   CALL ASNLUN(2, 'ST'), 0, IDS)
   IF(IDS.NE. 1) WRITE(TTY, 100)IDS
   100 FORMAT(1H, 'Tablet ASNLUN error. Status: ', I5)
C -- -- -- NORMAL ENTRY POINT FOR DIGITIZING -- --
ENTRY DGT(STATUS,STBUF)
C
C Prompt user with tty bell (ctrl-g)
WRITE(TTY,101)
101  FORMAT(1H, 'Ready to accept a data point when the bell sounds. ')
C Sound the bell
102  CALL GETADR(PARAM(1),BELL)
    PARAM(2)=1
    PARAM(6)="40"
    CALL WTQIO(WLB,TTY,1.,IOSB,PARAM,ISB)
C
C Issue read to tablet device, and check for error status
1000 CALL GETADR(PARAM(1),STBUF(1))
    PARAM(2)=6
    CALL WTQIO(RLB,2.1.,IOSB,PARAM,IDS)
    IF(IO SB(1).EQ.1)GO TO 106
100  C
200  C Exit on all device errors except power off
300  WRITE(TTY,104)IDS,IOSB
400  104  FORMAT(1H, 'Tablet device error. Directive and I/O status: ',I7,1 '
    1 ',',207)
500  IF(IO SB(1).NE."375")GO TO 109
600  WRITE(TTY,105)
700  105  FORMAT( '$Turn tablet power on and hit carriage return.' )
800  READ(TTY,103)IDO
900  103  FORMAT(AA)
100  GO TO 102
C
C Successful read from tablet-check for flags
1000  106  STATUS=0
200  IF(IAND(STBUF(1),"100000").EQ."100000)STBUF(2)=-STBUF(2)
300  IF(IAND(STBUF(1),"400000").EQ."400000)STBUF(3)=-STBUF(3)
400  IF(IAND(STBUF(1),"4000").EQ."4000)STATUS=1
500  IF(IAND(STBUF(1),"2000").EQ."2000)STATUS=2
600  IF(IAND(STBUF(1),"1000").EQ."1000)STATUS=3
700  RETURN
C
C Error exits
100  109  CLOSE(UNIT=3)
200  STOP 'UNKNOWN DEVICE PROBLEM.'
0.1 //CONDOR JOB (HU.JJB) TIME=(2)
0.2 // EXEC WATFIV
0.3 //FT12F001 DD DSN=WYL.HU.JJB,PERM.ST.PETE,UNIT=DISK,
0.4 // DISP=SHR,Vol=SER=PUB007
0.5 //FT13F001 DD DSN=WYL.HU.JJB,READY,UNIT=DISK,
0.6 // DCB=(RECFM=FB,RECL=90,BLKSIZE=1000),
0.7 // DISP=(NEW,KEEP),SPACE=(TRK,(13,2),RLSE),
0.8 // VOL=SER=PUB007
0.9 //SYSIN DD *
1. C --- --- - CONDOR PROGRAM - --- -
2. C PROGRAM DESIGNED TO TAKE OUTPUT
3. C FROM SURFACE II AND CONVERT IT TO
4. C FORM NEEDED BY THE MODIFIED TRESSEXT MODEL.
5. C --- --- - BEGIN PROGRAM - --- -
6. DIMENSION A(100,100),FAC(100,100),C(100,100)
7. FACT = 1.00
7.1 C --- READ GRID CHARACTERISTICS AND NODAL VALUES FROM
7.2 C --- --- --- --- --- --- "SURFACE II FILE" --- --- ---
7.3 READ(12,5) NCOLS,NROWS
7.4 WRITE(6,6) NCOLS,NROWS
10. DO 1 DO I=1,NCOLS
11. READ(12,10) (A(I,J),J=I,NCOLS)
12. WRITE(6,10) (A(I,J),J=I,NCOLS)
12.1 DO 100 J=I,NCOLS
12.2 C(I,J) = 0.0
13. 100 CONTINUE
13.1 C --- ROUND OFF NODAL VALUES AS REQUIRED BY
13.2 C --- --- "THE MODIFIED TRESSEXT MODEL" --- ---
14. DO 110 I=1,NROWS
15. DO 110 J=1,NROWS
17. FACT(I,J) = AINT(A(I,J))
17.5 IF(A(I,J),GT.0.0) GO TO 105
18. IF(ABS(A(I,J) + FACT(I,J)),GT.0.5) FACT(I,J) = FACT(I,J) - 1.0
18.5 GO TO 110
18.6 105 IF(A(I,J) - FACT(I,J),GT.0.5) FACT(I,J) = FACT(I,J) + 1.0
18.7 CONTINUE
19.1 C --- WRITE TRANSFORMED NODAL VALUES TO MODIFIED
19.2 C --- --- "TRESSEXT FILE IN F FORMAT" --- ---
19.3 WRITE(13,11) C(1,1),C(1,J),J=1,NCOLS,C(1,2)
20. DO 120 I=1,NROWS
21. WRITE(13,11) C(1,1),FACT(I,J),J=1,NCOLS,C(1,2)
22. WRITE(13,11) C(1,1),FACT(I,J),J=1,NCOLS,C(1,2)
23. 120 CONTINUE
23.2 WRITE(13,11) C(1,1),C(1,J),J=1,NCOLS,C(1,2)
23.5 5 FORMAT(2I6//)
23.6 6 FORMAT(2I6)
24. 10 FORMAT(10F9.3)
25. 11 FORMAT(16F5.0)
26. STOP
27. END
28. 4DATA
1. //GIVEME JOB (JD.JJB),REGION=SI2K,TIME=(1,2)
2. // EXEC WATFIV
3. //FTI2F001 DD DSN=WYL.JD.JJB.HOPE,UNIT=DISK,
4. // DISP=SHR, VOL=SER=PUB007
5. //FTI1F001 DD DSN=WYL.JD.JJB.GIVEN,UNIT=DISK,
6. // DISP=(NEW,KEEP), VOL=SER=PUB007,
7. // SPACE=(TRK.(3,2), RLSE),
8. // DCD=(RECFM=FB, LRECL=90, BLKSIZE=1800)
9. //SYSIN DD *
10. C -- GIVEME PROGRAM --
10.1 C -- PROGRAM DESIGNED TO TAKE BINARY OUTPUT --
10.2 C -- FROM SURFACE II AND CONVERT IT TO E FORMAT --
10.3 C -- TO ALLOW USER MODIFICATION AND REVIEW. --
10.4 C -- BEGIN PROGRAM --
11. DIMENSION A(140,140)
11.1 REWIND 12
11.5 C -- READ GRID CHARACTERISTICS FROM SURFACE II FILE AND
11.6 C -- WRITE THEM ONTO NEW FILE IN E FORMAT.
12. READ(12)NCOLS,NROWS,IZERO
13. WRITE(13,10) NCOLS,NROWS,IZERO
14. WRITE(16,10) NCOLS,NROWS,IZERO
15. READ(12) NC, NR, DC, DR, XL, XR, YB, YT, ZMIN, ZMAX, ZMIS
16. WRITE(13,11) NC, NR, DC, DR, XL, XR, YB, YT, ZMIN, ZMAX, ZMIS
17. WRITE(16,11) NC, NR, DC, DR, XL, XR, YB, YT, ZMIN, ZMAX, ZMIS
17.5 C -- DO LOOP WHICH READS NODAL VALUES FROM SURFACE II FILE
17.6 C -- AND WRITES THEM ONTO NEW FILE IN E FORMAT.
18. DO 100 I=1,NROWS
19. READ(12) (A(I,J),J=1,NCOLS)
20. WRITE(13,12) (A(I,J),J=1,NCOLS)
21. 100 CONTINUE
22. 10 FORMAT(3I6)
23. 11 FORMAT(2I6,BFB.2/F8.2)
24. 12 FORMAT(9EIO.3)
25. STOP
26. END
27. $DATA