FIELD ASSESSMENT OF STREAM/AQUIFER INTERACTION UNDER SEMI-ARID CONDITIONS AND PROBLEMS WITH COMPUTER REPRESENTATION

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Colorado State University

Colorado Water Resources Research Institute

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1. INTRODUCTION

As the population increases and technological development grows in Colorado, problems with the appropriation of water are becoming more serious and common. Surface water rights are particularly difficult to obtain, so groundwater is becoming especially important to newcomers and entities with junior water rights. The relationship of groundwater use to stream discharge is well known, but difficult to quantify. Groundwater models have attempted to address the problem, but while some promising new codes have been developed, they have not been adequately tested and are not generally used.

A field area in Golden, Colorado containing a small, ephemeral stream was studied with the aim of specifying problems associated with the modeling codes used in the area of stream/aquifer interaction. Field data describing the streamflow, streambed hydraulic conductivity, aquifer hydraulic conductivity and aquifer hydraulic heads were available (Anderman 1993, Anderman & Poeter 1993), and data regarding streambed and aquifer geometries were collected. The scale and types of data collected were chosen to obtain information regarding flow and gradients across and surrounding the stream boundary. This information was used to construct and calibrate a MODFLOW groundwater flow model.

MODFLOW mathematically models a three dimensional area in steady state or transient modes. The area is discretized into a three dimensional grid to which boundary conditions are set on all sides. Each grid cell is assigned parameter values. The model calculates the hydraulic head and the flow into and out of each grid cell.

The Streamflow Routing Package (Prudic 1989) was used as the stream module in MODFLOW. This package is more an accounting program, tracking the flow in streams interacting with the groundwater, than a true surface-water flow model (Prudic, 1989). It allows the user to specify the stream stage or to have the code determine the stream stage. This second option is an improvement on the original MODFLOW river module. The original module used constant stream stages; it calculated the seepage between the groundwater system and the stream, but did not allow the stream stage to vary in response to seepage.

The temporal nature of the system must be input to the model. If the model is transient, the time elapsed is divided into stress periods, and each stress period is divided into time steps. The user can specify changes in some of the parameters at the end of a stress period if necessary. At the end of every time step, information about the state of the model, for instance the values of heads and flow rates, can be printed in the output file.

The site geometry is input to the model in the form of a discretized, three dimensional grid. This grid is constrained on all sides (and if necessary in places interior to the grid) with boundary conditions that may include no-flow, specified flux, constant head, head-dependent flux, or free surface boundaries. Each layer is defined as a specific layer type: confined, unconfined, or convertible. Each grid cell is assigned a hydraulic conductivity, both horizontal and vertical; as well as a storage coefficient and a specific yield if the grid cell corresponds to an unconfined layer. As appropriate, hydraulic features are assigned to cells (e.g., pumping or injection wells, recharge, drains, and stream reaches). Using the above information, MODFLOW mathematically simulates the flow through and the head in each cell for each time step or for steady state, whichever is applicable.

Once the model has been set up, it must be calibrated. During this process the simulated heads and flows are compared with the field measurements. If they do not match within specified limits, the parameters used in the model are adjusted to better approximate these measurements, while remaining within reasonable physical ranges.

MODFLOWP (Hill, 1992) is a version of MODFLOW that includes a parameter estimation package and was used in the calibration process. MODFLOWP compares the estimated and the measured data as described above. The program then calculates an objective function which describes the difference between simulated values and field measurements. The hydrogeologic parameters are re-estimated so as to minimize the objective function, the model is re-run, and the field measurements and calculated values are compared again. This process is repeated until the parameters are no longer changing more than a specified tolerance.

The results of the calibration process were used to identify problems with the model. Some of these problems were caused by poor data coverage which led to uncertainty in the conceptual model used in the modeling process. Shortcomings of the codes also contributed to problems with the modeling process. All the above are explored and discussed later.

Recommendations for future work are included as part of that discussion. Work at this field area is ongoing.

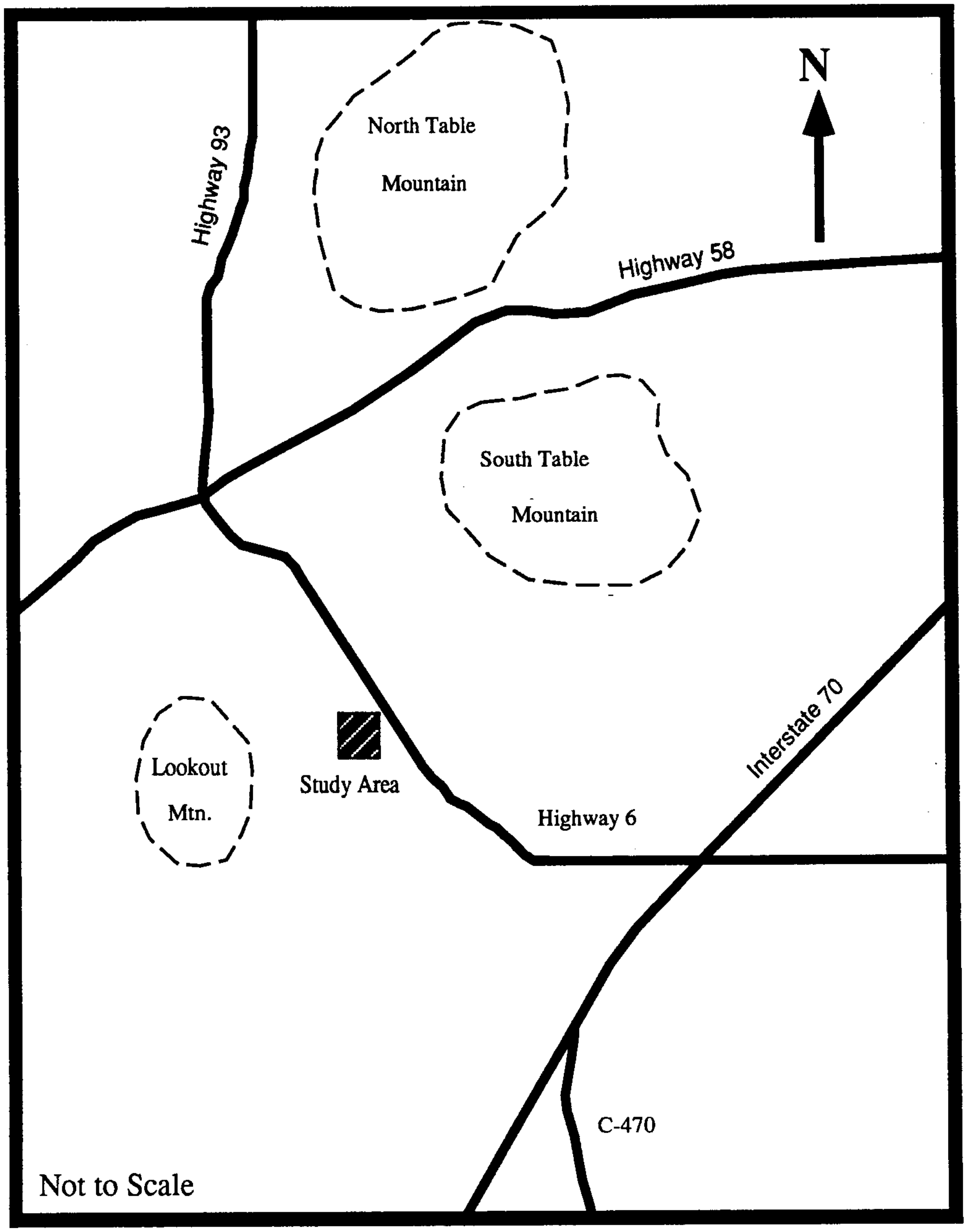
2. FIELD STUDY

Study Area Description

A small ephemeral stream was studied for the purposes of this project. The stream, a tributary to Kenney Run, is located in the Colorado School of Mines Survey Field approximately one mile southwest of the main campus in Golden, Colorado (figure 2.1). The stream flows for several months of the year, but is small enough that the flow can be measured without great expense.

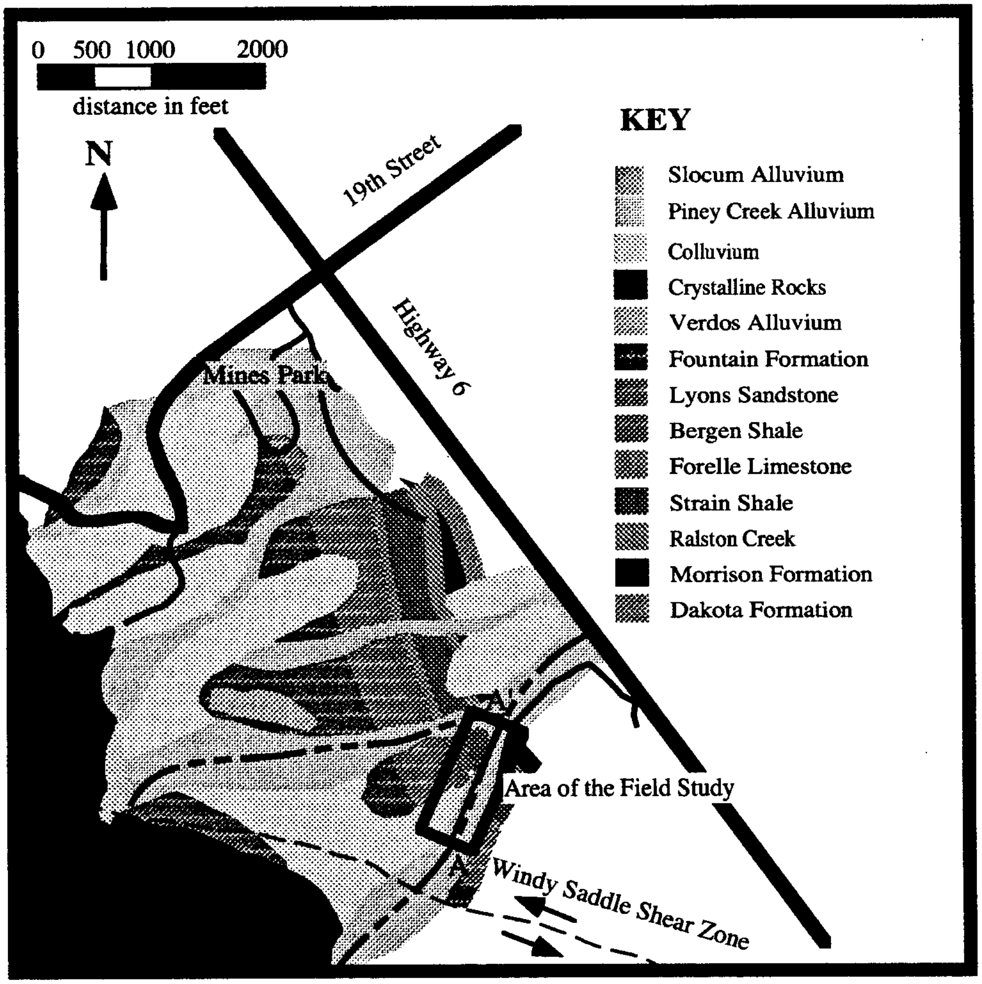
The site is small, approximately 1200 feet by 400 feet, with the stream flowing lengthwise through the center of the area. The stream reach is 1500 feet long within the area, occupying a small valley that slopes down from Lookout Mountain. The valley is composed of poorly sorted colluvium with grains ranging from clay to boulder size.

At least seven sedimentary formations underlie the colluvium. They range from Pennsylvanian to Upper Cretaceous in age and include the Fountain Formation; the Lyons Sandstone; the Lykins Formation which has been subdivided into the Bergen Shale, the Forelle Limestone, and the Strain Shale; the Ralston Creek Formation; the Morrison Formation; and the Dakota Group (figure 2.2) (Scott, 1972). The Fountain Formation consists of a 1650 foot thick maroon, arkosic, thick-bedded, coarse-grained sandstone and conglomerate which is Pennsylvanian in age. The Permian Lyons Sandstone is a 190 foot thick yellowish-gray conglomerate that grades downward to a fine-grained sandstone. The Bergen Shale is composed of a Permian, 133 foot thick, maroon and green siltstone. The Forelle Limestone, also Permian, consists of a pink, wavy, laminated, sandy, marine limestone about 17 feet thick. The Triassic Strain Shale is a member of the Lykins Formation and includes a fine-grained silty sandstone, and a siltstone, 300 feet thick. The Upper Jurassic Ralston Creek Formation is composed of a sandstone, underlain by sandstone containing some limestone, and is 90 feet thick. The Morrison Formation includes siltstone, sandstone, and limestone beds; it is approximately 300 ft thick and was deposited in the Upper Jurassic. The Lower Cretaceous Dakota Group consists of a tan to light yellowish gray, medium-grained, cross-bedded sandstone



General Location of the Study Area

Figure 2.1



From the Geologic Map of the Morrison Quadrangle

Glen Scott, 1972, USGS, 1:24,000

Study Area Geology

Figure 2.2

with interbedded siltstone and claystone (Scott 1972; Anderman 1993; Anderman and Poeter 1993).

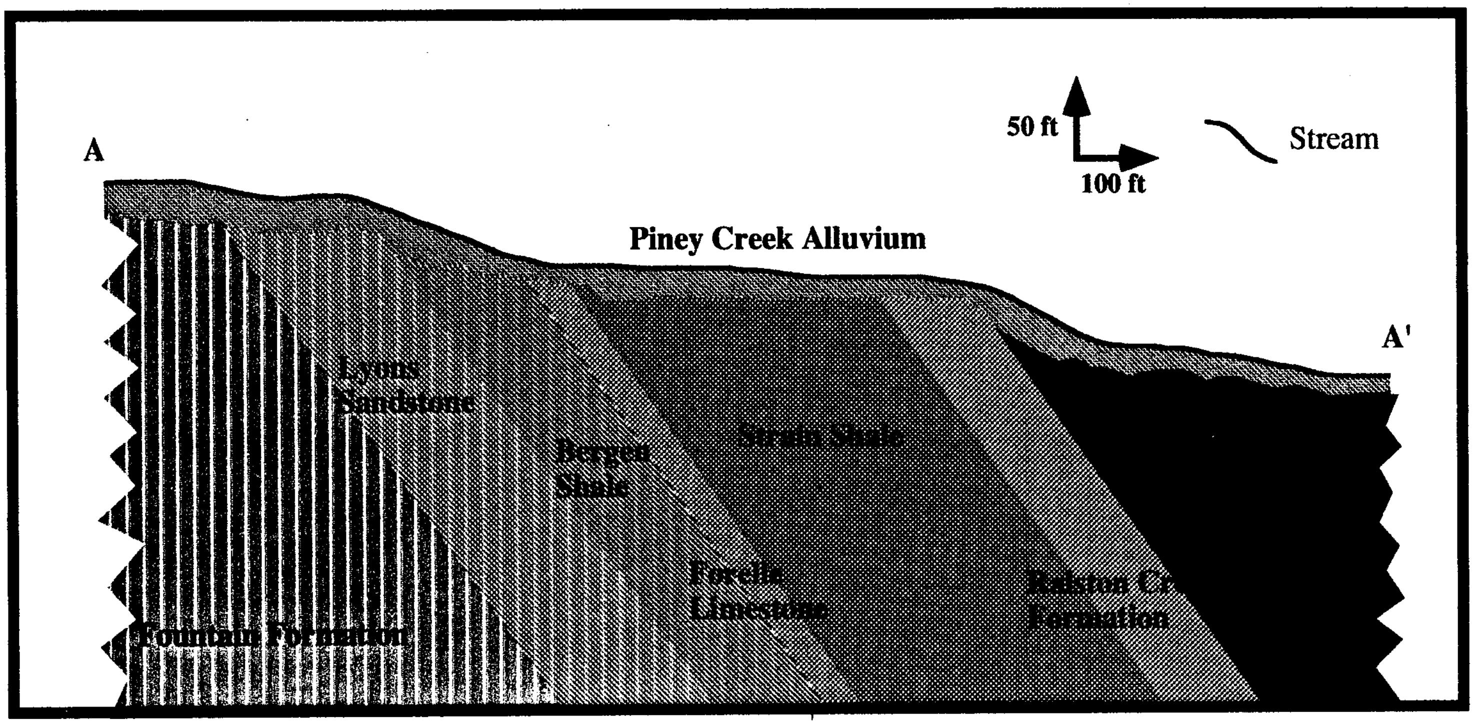
The area is located between the first line of foothills of the Rocky Mountain Front Range and a sandstone hogback. Figure 2.3 shows a cross section taken along A-A' (a transect shown in figure 2.2). These formations are thought to lie at a steep angle because of the proximity of the uplift block. The streambed consists of Upper Holocene Piney Creek alluvium, composed of clayey silt and sand with layers of pebbles. In the Morrison Quadrangle, this alluvium ranges from 5 to 20 feet (Scott 1972).

Another study of this stream reach has been conducted concurrently (Anderman 1993; Anderman and Poeter 1993). Data relating to hydraulic head, stream flow, and aquifer and streambed permeability were collected and conclusions were drawn regarding the relationships between these parameters.

The site receives an average of 21 inches of precipitation per year (11 inches between April and October) (Hanson et al 1978). Vegetation varies considerably in spite of the small size of the site. Species that use very little water such as yucca and opuntia, a small cactus, exist as well as cottonwood trees, reeds and poison ivy, which need considerable amounts of water to survive. The stream flows in late spring and early summer and remains dry during the rest of the year. Stream flow occurs at each end of the area while the center of the stream reach is almost dry. The vegetation distribution reflects dryer conditions near the center of the area. The vegetation further indicates that while the water table is close to the surface near the stream, conditions become extremely dry within 200 feet to either side of the stream.

Data Collection

A variety of data types have been integrated in this study. The site is so small that published maps have scales too large to provide the detail necessary to this study (geology and topography maps are generally a 1:24,000 scale). In addition, only one outcrop, or control point, is located in the study area itself. Consequently, much of the data needed were collected in the field rather than in a literature review. Geology, topography, permeability, stream flow, hydraulic head, geophysics, vegetation, evapotranspiration, and precipitation data were collected directly at the site.



From Anderman 1993

Geological Cross Section of the Area Taken Along A-A'

Figure 2.3

Topography

A plane table and aledaide were used to collect approximately 200 data points in the area. The map was contoured manually using both the control points and visual references in the field. The contour map was then digitized, and contoured in SURFER (Interprex). The SURFER plot was scanned into a Macintosh PICT file, which was then brought into Canvas to produce the map shown in figure 2.4. The gridded data from SURFER were used later in the MODFLOW and MODFLOWP input files.

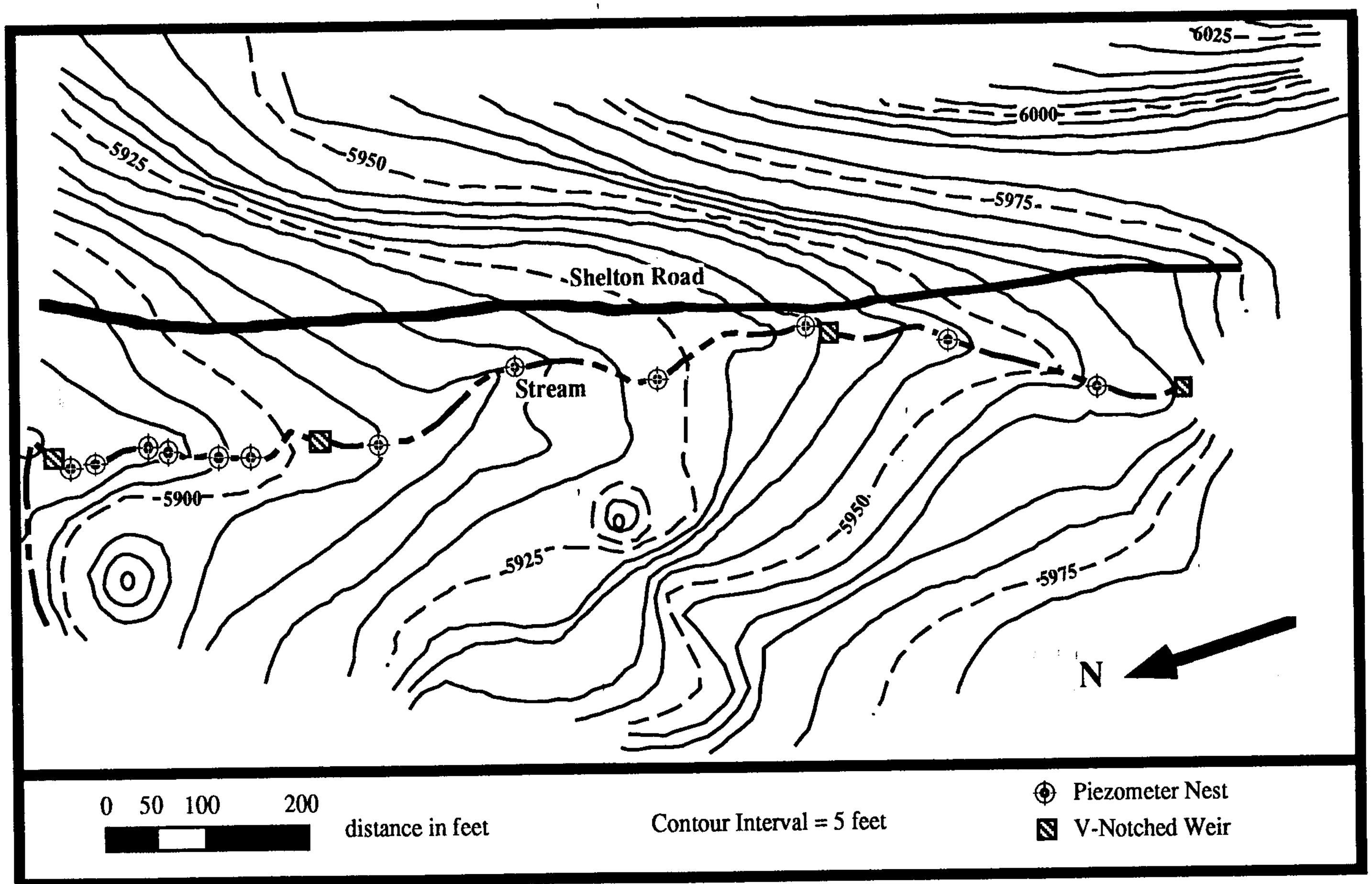
Permeability, Hydraulic Head And Stream Flow

Anderman (1993) and Anderman and Poeter (1993) analyzed the relationships between permeability, stream flow and hydraulic head at the site. Four weirs and 12 nests of piezometers were installed at locations shown in figure 2.4. The weirs and the piezometers were monitored from late spring to mid-fall of 1992 (Appendix A). Permeability was measured using slug tests in the piezometers, lab permeability tests, and field air permeameter measurements (Anderman 1992; Anderman and Poeter 1993). Problems were encountered in the slug tests due to fine-grained material getting into the piezometers, clogging them and causing erroneously low hydraulic conductivity measurements. Lab tests were suspect because the samples were disturbed. The air-permeameter measurements seemed to be the most reliable, and are presented in Appendix B. The problems with fine-grained material getting into the piezometers could have skewed the head measurements, so the measurements from the piezometers containing substantial amounts of silt were omitted from the calibration of the final model.

Geophysics

The depth to bedrock was determined using geophysical techniques. Electrical resistivity soundings were undertaken using Schlumberger arrays, and shallow seismic refraction lines were later run to complement the data. The field program was designed to determine depth to bedrock, depth to water table, and the location of geologic contacts.

A Schlumberger array consists of two current electrodes and two potential measuring electrodes. The potential measuring electrodes are placed a distance 'a' apart. The current electrodes are then placed in line with the potential electrodes and far enough



Topography, Piezometer and Weir Locations

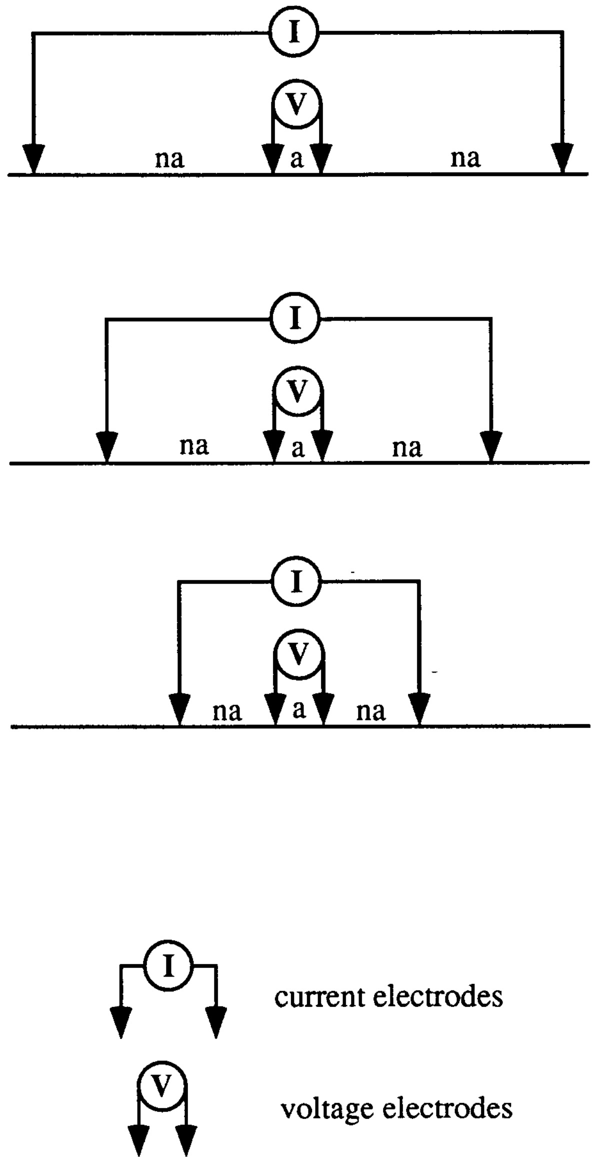
Figure 2.4

apart that the distance 'a' becomes negligible (figure 2.5). The potential measuring electrodes are kept in the same place and the current electrodes moved so that several measurements at different depths are taken over the same spot, giving a vertical resistivity profile, also called a sounding. This process was performed at several locations. The data was interpreted with RESIX (a Geometrix software program), but the resistivity data was of limited usefulness. The variable topography caused substantial 2-D effects creating problems with interpretation of the data. One sounding produced useful results (figure 2.6, Appendix E), but all other data had to be discarded. This sounding showed a depth of approximately 15 feet to bedrock. No other contacts or layering were found.

A twelve channel Geometrix seismograph was used with a sledgehammer as a source to delineate the depth to bedrock. The eleventh geophone was defective on all the shot lines, but did not significantly affect data interpretation. Two lines were shot to test the spacing. Geophones were 3 feet apart, and shots were made at 5, 10, 15, and 30 feet from both ends of the line. This spacing was too small to get the necessary detail, so the rest of the lines were run with geophones 4 feet apart, and the source at 4, 16 and 32 feet from either end of each line. The location of each line is shown in figure 2.6.

The major source of noise was wind. The geophones were often in contact with vegetation in the area, and were only two inches deep. Plant movement due to wind seriously affected the results and attempts were made to wait for the wind to die down before taking a reading. Sometimes this was possible and sometimes not. In all cases the process was repeated until the signal/noise ratio was high enough that first arrival picks could be made accurately.

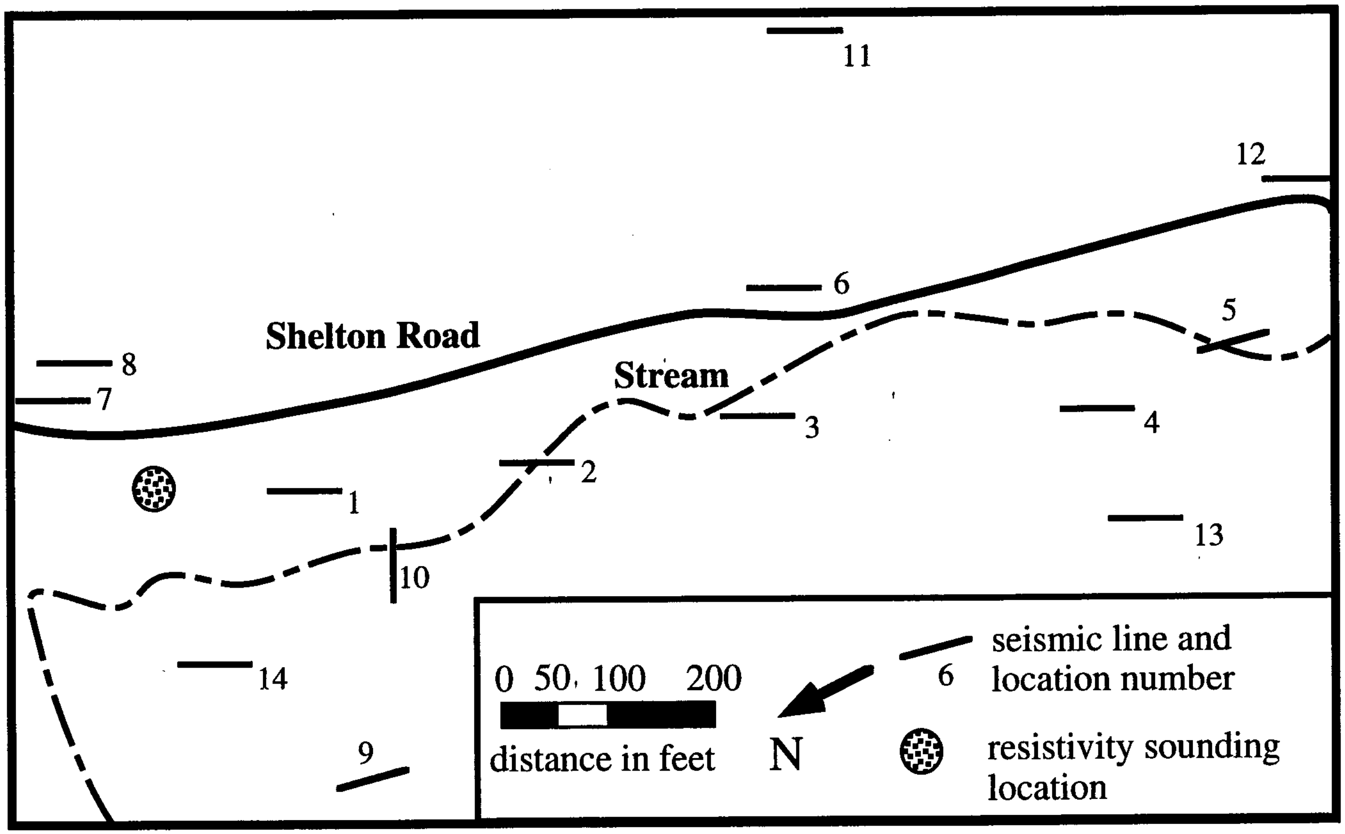
The results were interpreted using the program GREMIX, by Interprex Limited (Interprex 1990). The first arrival picks were made manually and entered into the program along with the elevation of each geophone and shot point (from the topographic map in figure 2.4). Arrivals were assigned to all shots and then reciprocal times were estimated automatically by the program (Appendix F). After the reciprocal times had been estimated, a velocity analysis was performed. Four methods of analysis were available: full generalized reciprocal method (GRM) velocity analysis, partial GRM analysis, optimum X-Y GRM analysis, and the time-delay method. The quickest and easiest is the time-delay method. It is also the first pass of the optimum X-Y analysis,



A Sclumberger array consists of two voltage electrodes placed a distance 'a' apart, and two current electrodes, one on either side of, and a distance 'na' (some multiple 'n' of 'a') from of the voltage electrodes. A Schlumberger depth sounding entails changing the position of the current electrodes (changing 'n'); the farther they are apart, the deeper the measurement, the closer they are together, the shallower the measurement.

Schlumberger Sounding

Figure 2.5



Geophysical Data Locations
Figure 2.6

which then uses the optimum X-Y values from this pass to perform a second pass using the partial GRM analysis (Interprex 1990).

The GRM (Palmer, 1980, 1981) can be used to process and interpret in-line seismic refraction data consisting of both forward and reverse travel times. An optimum XY distance (where the geophones are such that the forward and reverse rays emerge from nearly a common point on the refractor) is found using GRM. At such an XY distance, the velocity analysis will be the simplest and the time-depth sections will show the most detail. The conventional reciprocal method, which assumes an XY value of zero, can produce fictitious velocity changes and can produce an irregular refractor model. Use of the partial GRM analysis works well if one knows the appropriate XY values for each layer and refractor velocities are laterally homogeneous. Full GRM analysis is time-consuming and tedious, but is the most complete of the analysis methods. If there are lateral variations in refractor velocity, a full GRM analysis must be completed to obtain an accurate interpretation.

A full GRM analysis was completed for each seismic line. At the end of each analysis, both the observed and the calculated XY values were given by GREMIX. They must agree for the interpretation to be accurate. The interpretations of most of the initial seismic lines were straight forward. Seismic velocities were relatively uniform in the alluvium, but those in the bedrock varied considerably. It had been hoped that the differences in bedrock velocities would pinpoint the bedrock contact locations. But the bedrock velocities varied so much, probably because of the weathered upper portion of the bedrock, that it was impossible to find the formation contacts.

When the XY values do not agree, a hidden or masked layer is indicated. A hidden layer can be one that has a seismic velocity lower than the layer above it. This can cause seismic waves passing through it to arrive later than those from deeper layers, and the hidden layer is then difficult or impossible to detect. Manipulating the velocities or layer thicknesses so that the XY values agree, accommodates the hidden layer by using an average velocity for it and the overlying material (Palmer 1980). This manipulation will give a more accurate total depth to the important refractor, but it plays down the geologic significance of the overlying layers by averaging them together.

This situation was encountered in two of the initial seismic lines run in the area. The location, thickness, and velocity of the hidden layers found in these lines could not be determined with the available data. In this situation the lower velocity layer could be clay or it could be a better sorted, coarse-grained material. Either would have greater porosity and lower seismic velocity. A clay is likely to be less permeable and a well sorted material is likely to be more permeable. Hidden layers can also result from wetting fronts, as opposed to layering in the aquifer materials themselves. These possibilities complicate interpretation of the data for a hydraulic model.

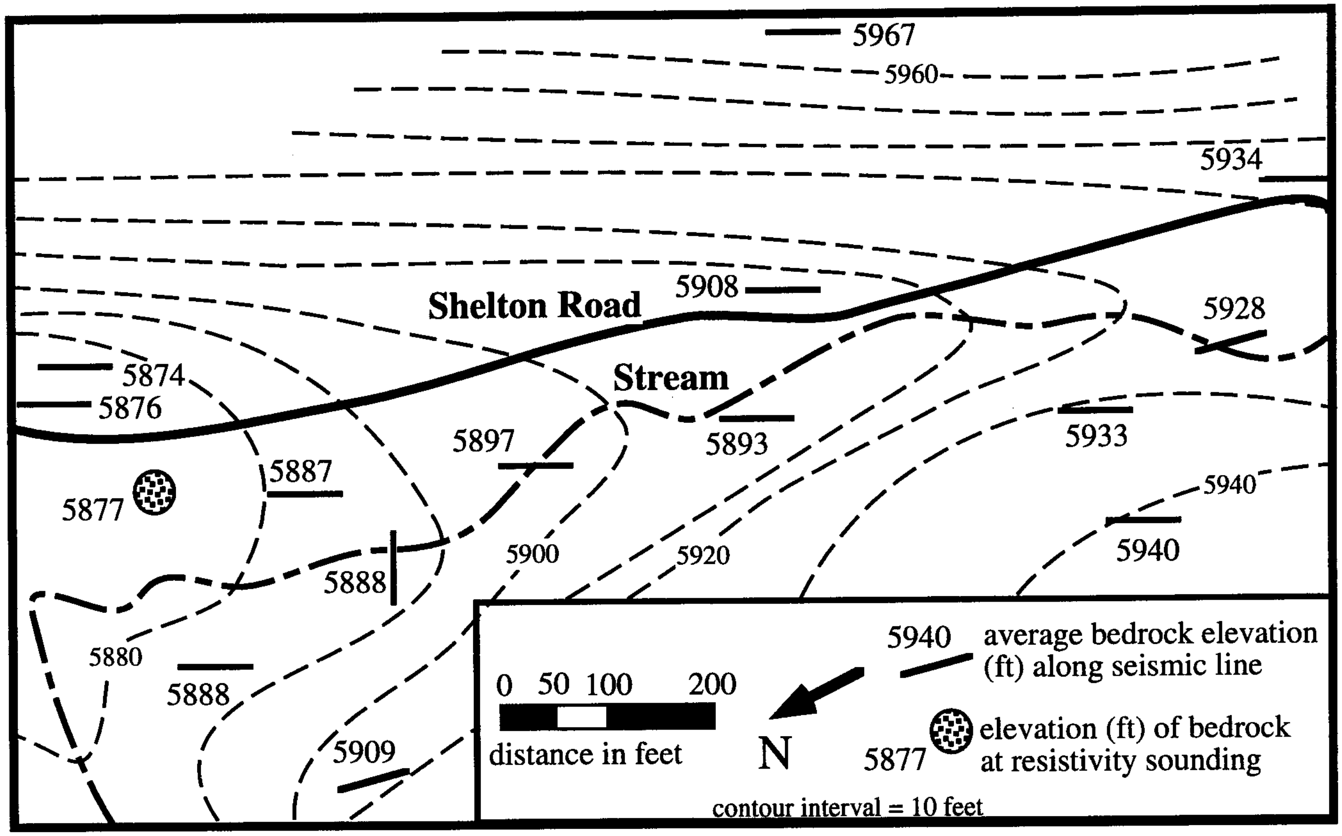
A drill hole would normally be required to calibrate the seismic data to "hard" measurements. However, the field budget could not accommodate a hole, thus the alluvium was subsequently modeled as a homogeneous material.

Eight additional seismic lines (figure 2.6) were run to constrain depth to bedrock at the site. All gave fairly good results, but hidden layers were found at a number of locations and resolution was not good enough to see the water table along any of the shotlines. Perhaps there was no water table to be seen in the alluvium at the time when the seismic surveys were undertaken in October, 1992..

In summary, the geophysical techniques gave excellent results for depth to bedrock, ranging from approximately 5 to approximately 33 feet, but could not define either the geological contacts or the location of the water table. The results of the geophysical surveys are shown in figure 2.7, the elevations shown for the seismic refraction lines are the average elevations along those lines.

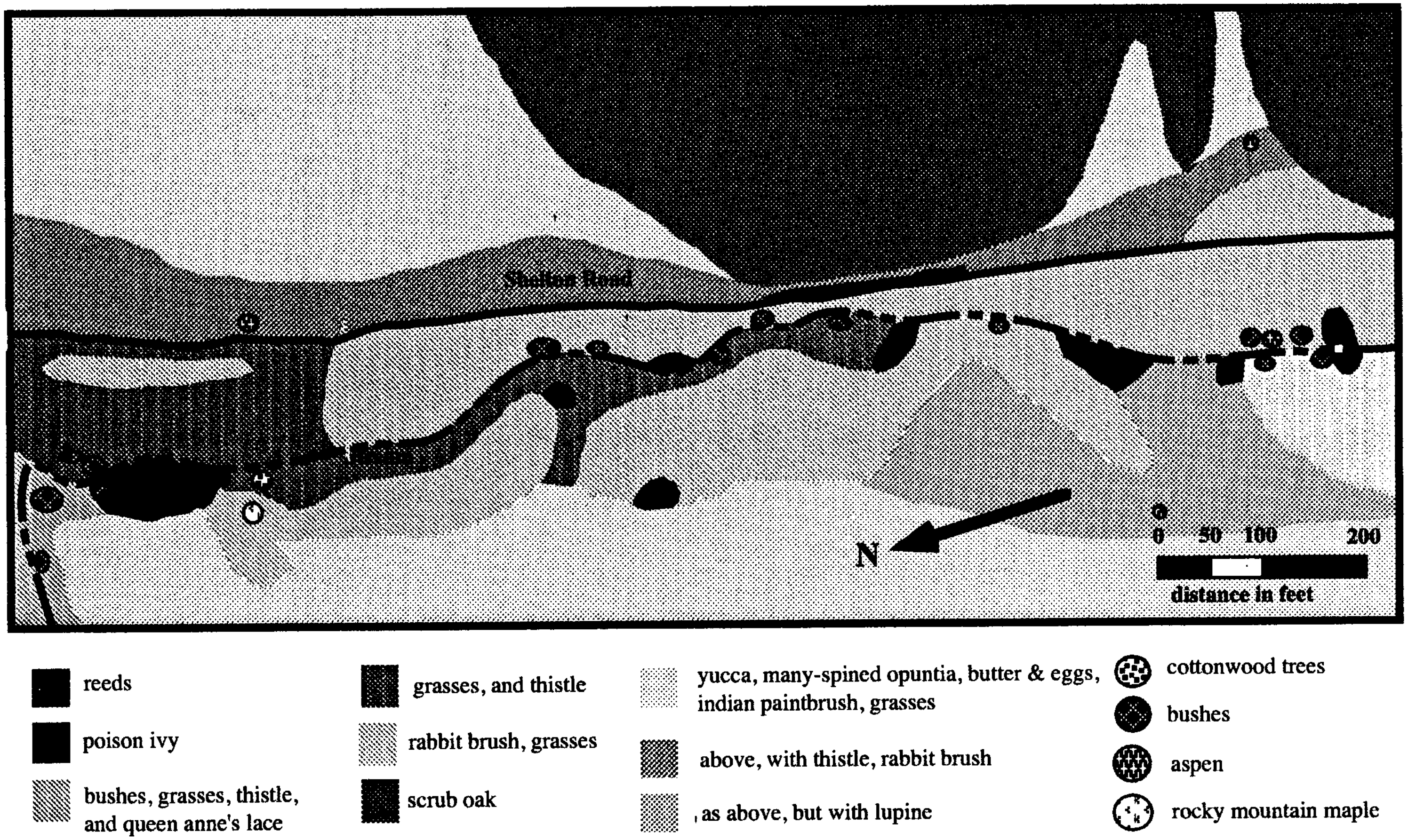
Vegetation, Evapotranspiration, And Precipitation

Vegetation was mapped in the area (figure 2.8). Several field guides (Curtis 1967, Brown 1979, Whitney 1982, Mutel 1984, Brown 1989) were used to identify the plant species. The vegetation exhibits extreme variation in evapotranspiration characteristics. Distant from the stream, vegetation consists of yucca, opuntia and some grasses, all of which use very little water. Poison ivy, cottonwood trees, reeds and other water use intensive plant species are concentrated near the stream. The vegetation map was used in conjunction with a literature review to make a first approximation of local evapotranspiration rates. Vegetation patterns were also used to estimate the boundaries of the saturated portion of the alluvium and to estimate depth to the water table for use in model calibration.



Geophysical Data Locations and Results

Figure 2.7



Vegetation Map

Figure 2.8

Summary of field data

The geometry of the area was well constrained in this project. This was done using surveying techniques to get a detailed knowledge of the topography of the site. The geophysics also gave excellent results regarding the depth to bedrock.

Many measurements of hydraulic head along the stream and streamflow were taken, however, for the purpose of creating a mathematical model, values from earlier in the spring were needed. Additionally, head data were needed at depths greater than three feet along the stream and at all depths away from the stream.

Hydraulic conductivity tests of the colluvium and of the streambed were conducted. These measurements were useful, but they were taken in a limited area (Anderman 1992; Anderman and Poeter 1993). The streambed material changes dramatically over the stream reach in the site, but streambed hydraulic conductivity measurements were only taken at locations corresponding to one material type (Anderman 1992; Anderman and Poeter 1993). The value of streambed hydraulic conductivity had to be estimated for the other material types. Horizontal aquifer hydraulic conductivity was measured to a depth of three feet in a few places, relatively close together. It will have to be estimated for zones deeper than 3 feet everywhere, and at all depths over much of the area. There were no measurements of vertical hydraulic conductivity. The vegetation information collected was useful in estimating the hydraulic heads and the hydraulic conductivity parameters.

Precipitation was well known for the area, but no information was obtained regarding the evapotranspiration values of the vegetation types found on the site. Therefore, recharge had to be estimated. Additionally, no information was collected concerning flow from and to the bedrock; the bedrock was assumed to be impermeable, but this may not be the case.

3. MODEL SETUP

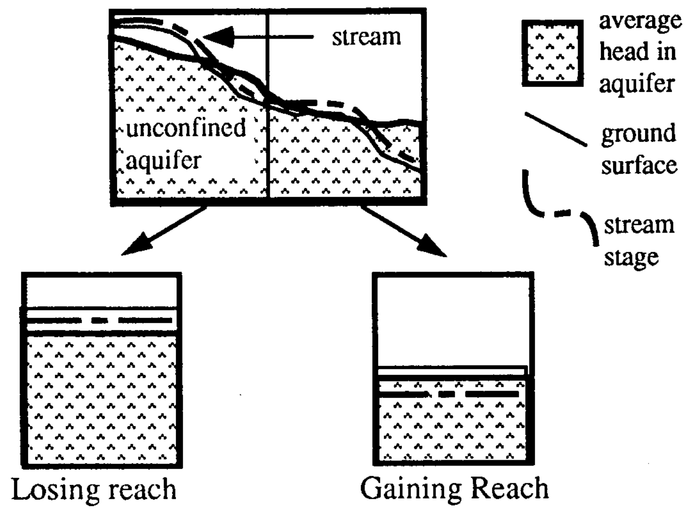
Conceptual Approach

Groundwater models can be made to any scale; the scale chosen will affect the input data requirements and the type and accuracy of the predictions made with the model. Degree of heterogeneity is an important consideration in the choice of model scale, with areas of greater heterogeneity requiring a more detailed model. At the basin scale, stream/aquifer interaction is one of many different processes operating, including precipitation, evapotranspiration, streamflow, groundwater flow, and artificial imports and exports to the system. The level of this study is large enough to incorporate these processes, but small enough to discern variations of streambed conductance and seepage. The data collection for this study was designed for a stream alluvium scale model.

Model boundaries are one of the most important aspects of model definition. In this area groundwater divides (topographic highs with small ephemeral streams on either side) appear to exist on either side of the valley (simulated as no-flow boundaries). Up and downstream boundaries were determined by the limits of data collection. The bottom of the aquifer was defined as the bedrock surface, and although there is probably some flow between the alluvium and the bedrock, it is assumed to be insignificant and thus defined as a no-flow boundary. An underlying unit often can be assumed to be impermeable, if it has a hydraulic conductivity more than two orders of magnitude less than the overlying unit and volume of flow in the upper unit is the topic of interest. Typically limestones and sandstones have hydraulic conductivity (K) approximately four orders of magnitude less than sand and silty sand (Freeze 1979). In this area the alluvium is similar to a sand or silty sand, and the bedrock is composed of sandstone and limestone units, so the bedrock is assumed to be impermeable. The alluvial aquifer is unconfined, so the top of the model is a phreatic surface. Recharge occurs predominantly during spring and early summer months from snowmelt and thundershowers, thus the top boundary is also a specified flux boundary. During the remainder of the year, recharge is thought to be near zero.

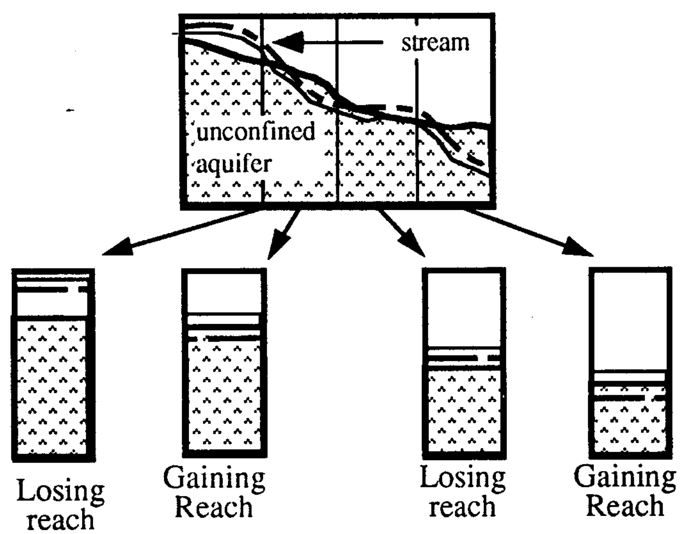
Small Losing And Gaining Reaches Are Differentiated By Narrower Cell Widths

Field Conditions and wide cells



wide grid cells average actual field conditions, with the possibility of blending losing and gaining portions of a stream together in one reach

Field Conditions and narrow cells



narrower cells reduce axial averaging, decreasing the amount of blending of losing and gaining reaches

Impact of Axial Grid Size on Seepage of Losing and Gaining Streams

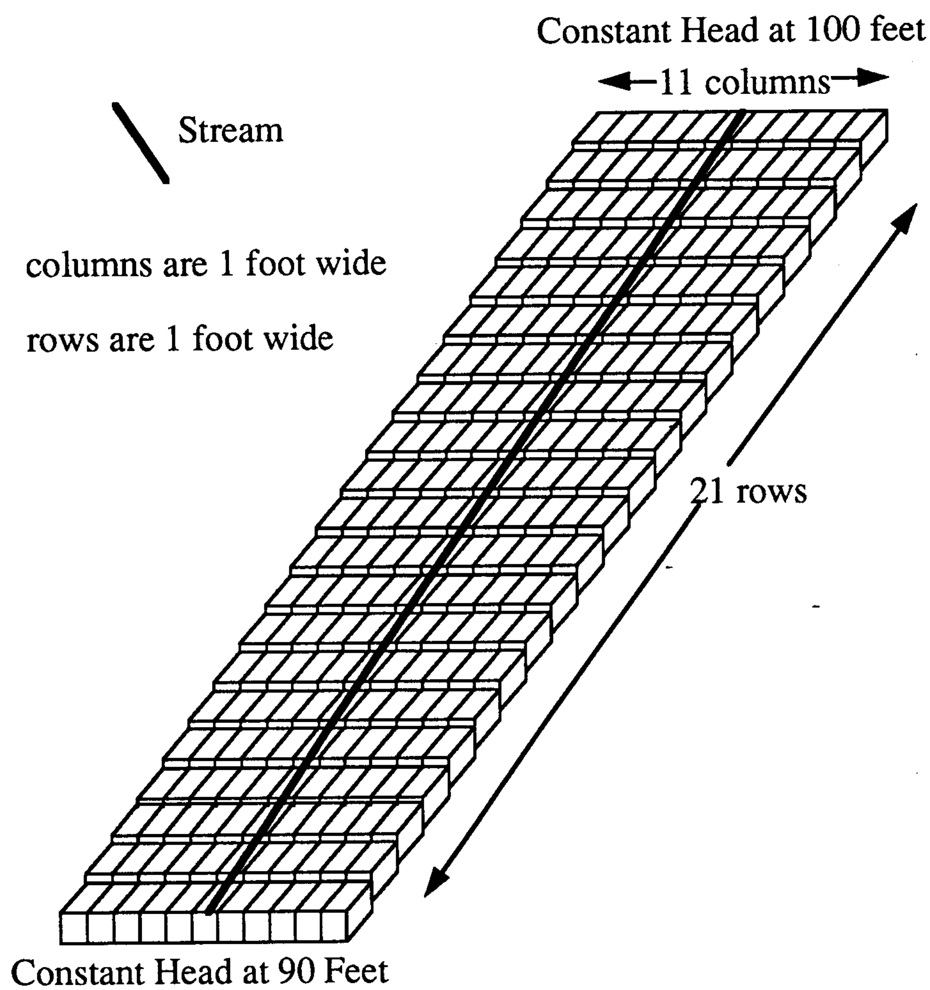
Figure 3.3

The finite difference method involves dividing the model domain into cells with straight lines forming squares and rectangles as shown in figure 3.4. If a stream were straight, it could be encompassed in one row or column, and cells could increase in size away from the stream reducing the number of cells in the grid while retaining detail at the stream. In a finite difference grid it takes less computational effort to simulate detail near a straight stream than a meandering stream.

With this in mind, a test was run, using MODFLOW, to evaluate the difference in head and stream seepage for a meandering and a straight stream, in the same hydrogeologic setting. The grids, model boundaries, and stream discretization are shown in figures 3.5 and 3.6. The resulting potentiometric surfaces are plotted in figure 3.7. Clearly, the resulting head distributions are virtually identical. In fact the largest head difference between the two runs is on the order of 10^{-3} meters (less than the tolerance for iteration of the solution). The flow into and out of each stream segment is presented in figure 3.8. The flow rates are very similar.

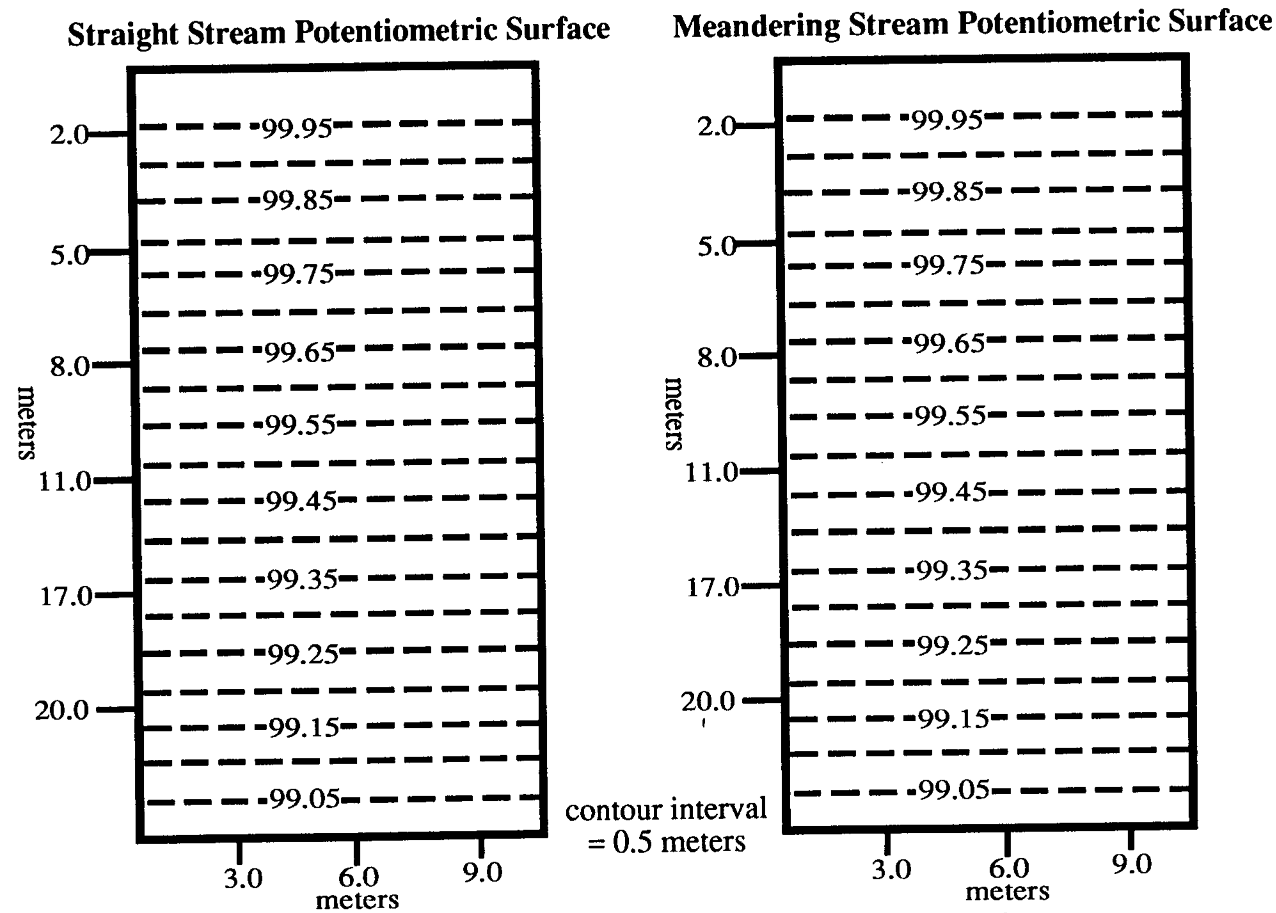
This test demonstrated that straightening the stream does not significantly affect model results in this situation, thus, a new, simplified, model grid was designed for this project in order to reduce computational time. The stream is represented as a straight line, allowing the grid to have one narrow column in the center where the stream is located and wider columns toward the sides with the constraint of limiting cells to less than 150% of the width of adjacent cells. The resulting grid is shown in figure 3.9. There are 112 rows, each 10 feet wide, and 10 columns with widths from left to right in feet: 50, 49 33, 22, 15, 10, 15, 22, 33, and 49. The sixth column (10 feet wide) contains the stream. The inactive cell locations are determined using the vegetation distribution, as discussed later. The system is represented with four layers. The top two layers are each 1 ft thick, corresponding to the depth of the first and second set of piezometers. The third is 4 feet thick, and the last is equal to the thickness of the remaining alluvium.

Straightening the stream for a field site is not as simple as doing so in the test model discussed above. The topography, alluvial thickness, vegetation type, recharge, and hydraulic conductivity distributions were adjusted laterally along each row by the same distance and direction as the stream was shifted. The vegetation is represented with 7 zones, each representing vegetation requiring similar water needs (figure 3.10). The inactive cell locations were determined by vegetation type as well. Areas with scrub oak



Straight Stream Test Grid

Figure 3.6



Meandering and Straight Stream Potentiometric Surfaces

Figure 3.7

magnitude higher. Slope of the streambed was calculated from the gridded topographic elevation values at cells containing the stream. Anderman (1993) and Anderman and Poeter (1993) mapped the streambed material and measured K in a few places with an infiltrometer. That K was used with a streambed thickness of 0.1 feet to calculate conductance where conductance is equal to the hydraulic conductivity times the area of the streambed divided by the thickness of the streambed.

As a first approximation, recharge was assumed to be 10% of the rainfall of 21 inches/year (Appendix C). The recharge may be even less as this is a semi-arid area. There also may be water entering from (or exiting to) the underlying bedrock (which, mathematically has the effect of raising or lowering recharge) rendering it difficult to estimate the net gain or loss to the system.

The boundaries at either end of the model were set by the general head boundary package (GHB). For the initial steady state model, the boundary heads were uniform and equal to the elevation of the streambed at the edge of the model.

How MODFLOWP is Different From MODFLOW

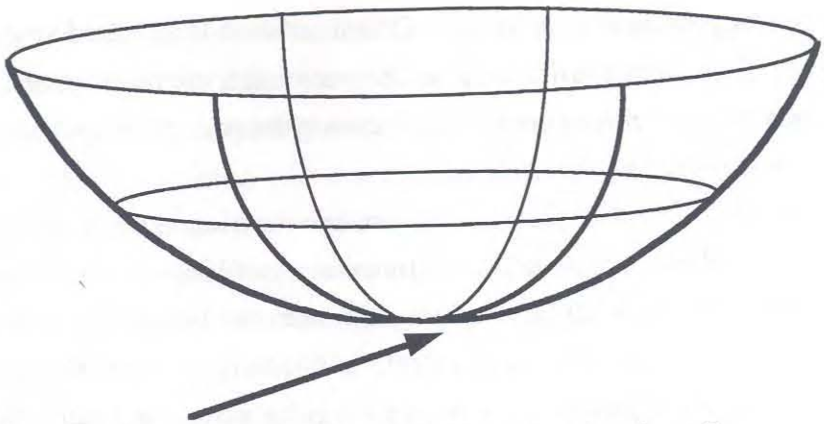
MODFLOWP is a new USGS code for inverse groundwater flow modeling, written by Hill (1992). This is a version of MODFLOW that estimates model input parameters by minimizing a least squares objective function using the modified Gauss-Newton or a conjugate-direction method (Hill, 1992). Until now, when MODFLOW was used to model an area, calibration had to be done by trial and error.

MODFLOW is a forward model; given parameter values and boundary conditions, MODFLOW calculates heads and flow rates. MODFLOWP is an inverse model; given heads, flow rates and an initial set of parameters and boundary conditions, it calculates parameters that minimize the difference between simulated and field measured values. The inputs to this type of model are: 1) fixed parameter values, these can be recharge, K, etc., that are considered known; 2) starting values of parameters to be estimated; and 3) observations of head and flow rate and their variances indicating the certainty associated with those measurements. MODFLOWP executes MODFLOW with the initial parameters, then compares the computed values of heads and flow rates to the observations. The parameters to be estimated are then adjusted to reduce the objective function which is directly related to the weighted residuals of heads, flow rates, and prior estimates of parameters. A MODFLOW simulation is executed again, and if the weighted residuals are still too large, the parameters are re-estimated. This process continues until the model converges, meaning the parameter estimates change less than a tolerance specified by the user.

In estimating the parameters from one iteration to the next, MODFLOWP strives to find the minimum of an objective function describing the weighted residuals. If the objective function is well behaved the minimum can be easily found. If it is not well behaved the minimum is difficult or impossible to find. A poorly behaved objective function is one that is either flat or very irregular, containing many different local minimums (figure 3.13). Good coverage, areally and temporally, of head and flow data will make a parameter estimation solution more unique, hence making the objective function better-behaved.

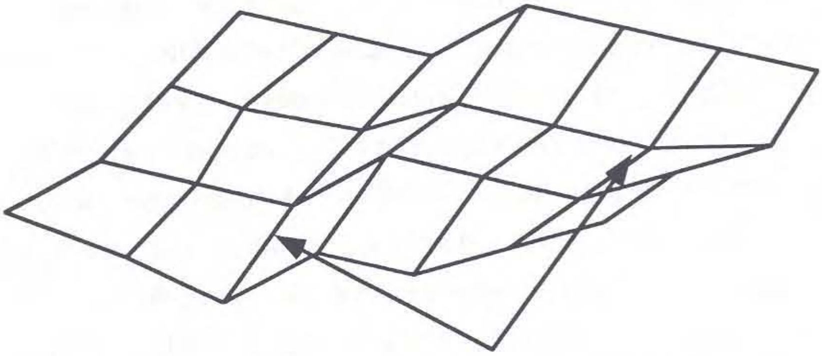
Although it is the maximum likelihood objective function that is used by MODFLOWP in the estimation process, many other statistical measures are performed and presented by MODFLOWP to allow the user to better analyze the model. Statistical measures of calculated head, flow, and estimated parameter residuals include range information and sum of squares weighted residuals. The standard deviations, coefficients of variation, and the correlation matrix of the estimated parameters are also included. As well, the calculated error variance and the correlation coefficient with and without parameters are among the statistics calculated by MODFLOWP. For a thorough discussion of these and other statistical measures used in MODFLOWP see Hill, 1992.

The weights given to prior estimates of the parameters being estimated are important for convergence in MODFLOWP. Without prior estimates the model can modify parameter values as much as is needed for convergence to occur. The result is truly an independently estimated parameter. However, due to the typical non-uniqueness of groundwater flow models a satisfactory convergence is rarely achieved without prior estimates. The weights are the inverse of the variances on the measurements of the parameters. In the case of an objective function describing an irregular surface, the inverse model may not be able to converge without tighter constraints on one or more of the parameters (figure 3.13). If this is the case, more accurate field measurements or better coverage of one or more of the parameters are necessary so that these tight constraints are valid.



The minimum is easily found when the function is well-behaved

The surface is close to flat, the minimum may cover a large area indicating that the parameters are correlated and a unique solution cannot be obtained with the available data.



There may be several local minimums on an irregular surface, making the solution non-unique

Common Characteristics of Maximum Likelihood Objective Functions

Figure 3.13

Parameters cannot be estimated accurately if the values calculated at all observation points are insensitive to that parameter, there are missing or inaccurate prior estimates, or the parameter is highly correlated with one or more other parameters. These problems can be avoided if the number of parameters estimated is minimized (Hill 1992). Coarse calibration should be done by hand before running MODFLOWP. If the starting values are too far away from the ending values and the objective function is not well behaved, the inverse model will not converge.

MODFLOWP was used to fine-tune the calibration of the steady state model. The model was set up to estimate vertical conductivity between layers, transmissivity of each layer, and general head boundary conductances. Various statistical measures are presented in the model output to give the user an unbiased way of determining the superiority of one model over another.

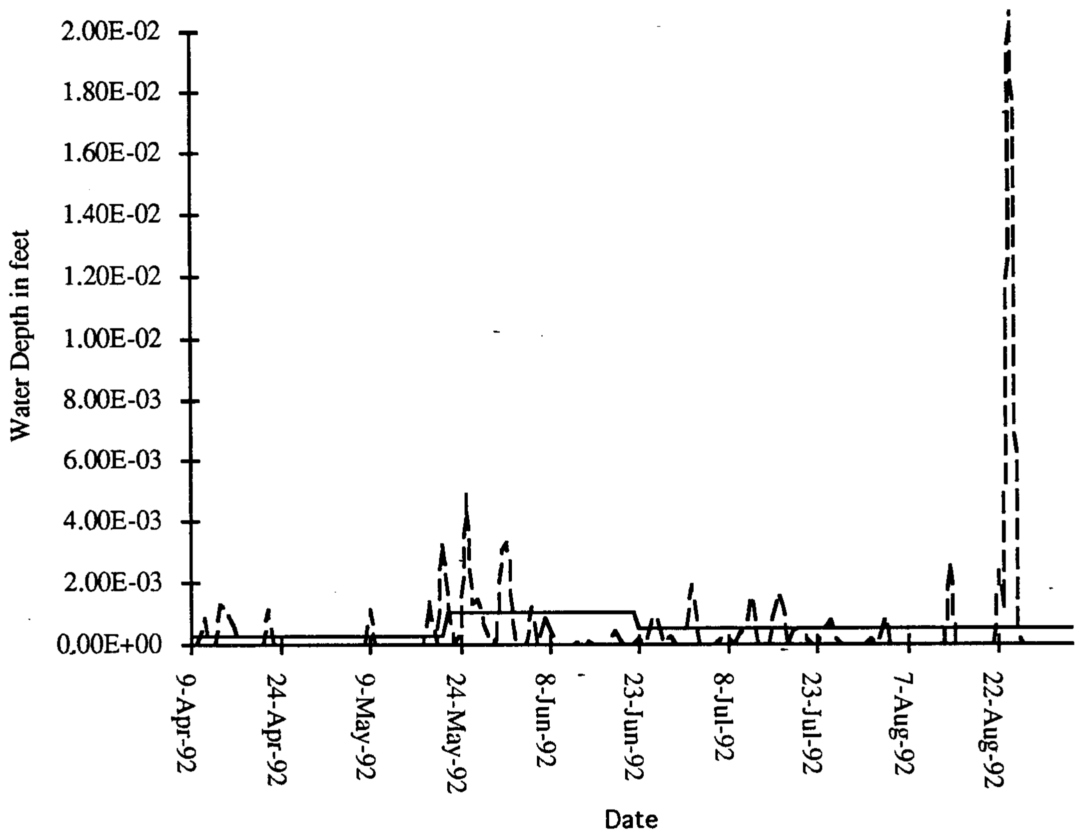
4. EXECUTION AND RESULTS OF MODFLOWP

Execution of MODFLOWP

In this model, the transmissivities and vertical conductivities were estimated. The vertical conductivities were estimated as one uniform value of vertical anisotropy over the entire extent of the aquifer. Distribution of K in the first two layers was represented by a zone array corresponding to the distribution of vegetation (see figure 3.10), assuming there is a correlation between vegetation and K (dryer vegetation corresponding to higher K). The third layer was represented with a uniform value of transmissivity (T), and the fourth layer was assumed to have constant K and a multiplication array corresponding to the thickness of each cell in that layer was used to calculate transmissivity.

While convergence was obtained for a steady state parameter estimation, the model had, for all practical purposes, been forced to converge. The variances on the prior estimates of the parameters were set to be extremely small (several orders of magnitude smaller than the estimates themselves). In addition, the pre-conditioned gradient solver (PCG) (Hill 1990) would not function with this model. It is not known why this was the case, but the strongly implicit procedure package (SIP) (McDonald 1988) did converge with a small acceleration factor and a large number of iterations. PCG is the solver suggested for use with MODFLOWP. The problem with using SIP for MODFLOWP is that it only calculates the seed for the iterations once, at the beginning of the entire run. MODFLOWP is complicated by MODFLOW interations as well as parameter estimation iterations, and repeated use of the same seed can prevent convergence. SIP is not an efficient solver for MODFLOWP (Hill 1992) although in this case convergence was achieved using SIP.

A transient model was constructed with 7 stress periods based on variation of precipitation (Appendix C). Recharge, estimated to be ten percent of the measured precipitation is presented in Figure 4.1. It is possible that recharge is less than 10% of precipitation considering the aridness of the area. In fact, a negative recharge (i.e. evapotranspiration greater than precipitation) is not unreasonable in this area. The net



straight line: simulated recharge
dashed line: 10% of actual precipitation

10% of Measured Precipitation Versus Time
Figure 4.1

recharge depends on the season and the nature of the vegetation; the time of day during which it falls; and character of the precipitation event (e.g., a light, long rain or a heavy, short downpour).

The transient model did not converge. Many combinations of SIP, PCG, various acceleration factors, tolerances, and prior estimate weights were evaluated. The model was simply too complicated and the data were too few to obtain a satisfactory parameter estimation. Each run required 3 to 12 hours of CPU time and large amounts of memory (output files contained upwards of 35,000 lines). It was attempted to initially calibrate the model using only the first stress period, then the second as well, and so on. This worked only for the first two stress periods, once the third was added convergence could not be achieved. Flow data was only available for the last three stress periods, so it was not included in the model with 1 or 2 stress periods. This was not acceptable, thus it was necessary to simplify the model.

The simplified model grid contained 10 columns (with the same widths as for the finer grid) by 28 rows (each 40 feet wide), and the same 4 layers as before. Problems related to averaging over the width of the cells were encountered (figure 3.3). The cells in this grid were 40 feet long, and considering that the stream was only about 2 feet wide, with stages of 1 foot above the streambed, at most, errors due to averaging caused relatively large residuals in stream stage and flow calculations. Thus, it was difficult to calibrate the model to the flow measurements. The PCG solver functioned on this new model set-up. The top layers went dry, and since all the head measurements were made at 3 feet or shallower, and the stream is located in the top layer, convergence was again not achieved. There were no flow measurements prior to the 4th stress period, therefore flow observations were not used in the parameter estimation because the run terminated before reaching the fourth stress period.

Another grid was constructed with two layers, the top layer was 3 feet thick and the bottom layer thickness encompassed the remainder of the alluvium. Only the last three stress periods of the original seven (so that all the stress periods used included streamflow measurements) were simulated. Convergence was achieved for this model, however, most of the top layer went dry early on, and consequently, most of the head measurements were excluded from the model. Because of this, many of the statistics were useless. For example, the head residuals had values equal to the thickness of the aquifer and standard deviations of parameter estimates were an order of magnitude greater than the estimates themselves. The estimated parameters could not be used.

The two-layer model was modified with the bottom layer having a K several orders of magnitude lower than the top layer to represent an impermeable layer. The top layer went dry and the model did not converge although many combinations of initial parameter values, solver parameters, and weights were evaluated.

A model was created with one thin layer 3 feet thick. Problems with this model include: with only one layer, vertical flow cannot be simulated; the vertical gradients that were measured cannot be used; and layering within the alluvium cannot be simulated. On the other hand, with only one layer, the entire model can be simulated as unconfined, which is representative of field conditions. However, convergence was not achieved.

A coarse grid with only one layer was employed again, but the entire thickness of the alluvium was included. K was estimated for four vegetation zones, conductivity of the streambed (KST) was estimated and GHB conductance's were also estimated. Convergence was achieved. All the measurements were included because the cells along the stream did not go dry. None of the parameters were strongly correlated with each other. Recharge was not estimated because convergence could not be achieved when estimating recharge. Once the model converged, recharge was modified slightly to decrease the head residuals.

A number of different models were constructed using this grid to determine the bounding limits of the estimated parameters. K was varied over 5 orders of magnitude, KST over 2 orders of magnitude, and recharge (RCH) over 2 orders of magnitude. The recharge, and to a lesser extent horizontal K, vertical K, and KST, could have been altered so that the heads would match better overall. However the parameter estimates were not reliable because the model has only one layer, represents steady state starting conditions, averages heterogeneities, and lacks sufficient observation data.

The one-layer finer grid was evaluated again. The same number of rows (112) and columns (10) were included to decrease spatial averaging. The objective was to facilitate calibration, but the objective was not met. The same problem with the starting heads was found; the steady state heads did not match the heads at the beginning of the transient run with less than 5 foot residuals. Since the stream stage is always less than 1 foot, this is not accurate enough. The results of the simulations with this fine grid were similar to those with the coarse grid. Without the ability to simulate vertical gradients through layering in the aquifer, and without more information regarding the vertical gradients below 3 feet, it was not possible to get the starting heads (from the steady state run) to match those measured in the field more accurately.

Two changes were made in the next modeling attempt. The GHB conductivity was no longer estimated, as the sensitivities calculated by MODFLOWP showed that the model is not sufficiently sensitive to that parameter. Additionally, the model was run with a coarse grid and all four layers, but all four layers were simulated as confined layers to keep them from going dry. All the parameter information was averaged and estimated over the entire area to obtain rough estimates of the parameters using a simplified model, but the layering was retained to allow for simulation of vertical gradients. A transient simulation was conducted with confined layering, one transmissivity, one recharge, one vertical conductivity, and one streambed conductivity for the entire model. When the transient model was running adequately, it was anticipated that the simulation would be run with an unconfined condition in the top layer.

This simulation converged. However the parameter estimates, while statistically sound, were not sensible. Recharge rose to fifteen times its original estimate, making it larger than precipitation. It had been expected that recharge might be less than the estimate of 10% of precipitation, it is possible for it to be larger than precipitation if there is water inflow from the bedrock, or if surface overland flow collects at the stream valley. However, recharge greater than an order of magnitude higher than precipitation is more than would be expected even for this scenario. Correlation between the estimated parameters was high. These high correlations indicate that more head and flow observations and/or better field measurements of parameters are needed. In addition to the high estimate of recharge, this model also estimated vertical conductivity as larger than horizontal conductivity, and this is not reasonable for layered fluvial deposits.

The final model was run, still with no prior estimates and with recharge fixed at 10% of precipitation. Horizontal hydraulic conductivity values increased from 57.2 ft/day to 3640 ft/day and vertical conductivity values decreased from .02 ft/day to .008 ft/day, increasing the anisotropy. Streambed conductivity values were lower (.07 ft/day instead of 6 ft/day. It is possible that the field hydraulic conductivity measurements were taken in a portion of the aquifer that is relatively fine-grained and that more gravel exists at depth. The bulk value would therefore be higher than the field measurements. The vertical hydraulic conductivity cannot be known without more data. The final streambed conductivity estimate was of the same order of magnitude as the measured values. Overall the results were acceptable, and were input to a transient model.

Parameter Estimated	**prior estimate**	**estimated value**	**standard deviation**
horizontal hydraulic conductivity (layers 3 and 4 estimated only, layers 1 and 2 were fixed)	57.2 ft/day	3640 ft/day	2310
vertical hydraulic conductivity (bulk value for the entire model)	0.0236 ft/day	0.00833 ft/day	0.0223
hydraulic conductivity of the streambed (multiplied by an array corresponding to material type)	6.13 ft/day	0.0761 ft/day	0.0226

Final Model Results

Table 4.1

As before, only the last three stress periods were used for the simulation, but all three sets of piezometer measurements could be included since four layers were used. At first, no prior estimates were included, and convergence was not possible. The prior estimates were then weighted, with standard deviations of the same order of magnitude as the respective values. For example, for the recharge value of 2.1 inches/year, the standard deviation was set to 1.0 inch/year. This standard deviation is used by the program to weight the initial guess of 2.1 inches/year. The value could vary easily from 1 to 3, but it would be less likely to become substantially less than one, or greater than three. In this case the model converged easily with these constraints but not at all without them. The results of the model are shown in table 4.1. The statistical measures associated with the model were good. The residuals, while still large (head residuals equal to the thickness of the aquifer) were as low as the lowest that could be found with the preceding simplified model and the other available measures were also as good or better than those of the preceding model.

Outcomes of Inverse Modeling

This is not a satisfactory inverse modeling exercise. The smaller the residuals are, the better the fit. The residuals of this model were the smallest found, but were nevertheless huge, head residuals the thickness of the aquifer, and flow residuals significantly larger than the measurements. The standard deviation of each estimated parameter was of the same order of magnitude as the estimated parameter value. For example, the vertical conductivity estimate was 0.008, and the standard deviation was 0.02. These standard deviations indicate great uncertainty about the estimated values. These results attest that the model is not accurate and the estimate values cannot be used.

Part of the reason for the unsuccessful modeling may be that many of the parameters were not well known. Recharge was fixed, and vertical conductivity was tightly constrained to allow the model to converge, even though those parameters are not well known. If one or more of the parameters were better known and could be fixed or tightly constrained, convergence with less constraint on the other parameters would be possible, and the results would be more credible. Two important parameters (recharge, and vertical conductivity) were fixed or constrained, therefore what is estimated is the relationship of the parameters that are being estimated to those that are not being estimated. Adjustments of parameters might better reflect field conditions but available data cannot be used to justify one alternative parameter set over another. For instance, K could be varied for different layers and could be varied within individual layers as well. During this project, horizontal K was varied for the top two layers using zone arrays. However there was no statistical difference between models with varying horizontal K in the top two layers and models with homogeneous horizontal K in those layers. Thus the simpler case, homogeneous K in the top two layers, was used. Vertical conductivity and streambed conductivity could also be varied spatially. Recharge could not only be varied areally, but temporally as well. With the data available and the limitations of the model itself, it would be unrealistic to conduct the simulation at a greater level of detail.

The modeling problems are also due to limitations of the codes used, such as the need to use a steady state starting point because grid cells cannot rewet. The system never reaches steady state. A steady state model must therefore use hypothetical conditions, which may or may not correspond closely to reality. To model this area properly, the simulation should begin with dry winter conditions and the water levels should rise with the spring recharge. The water levels would then drop as conditions dried through the summer and fall. To create such a model, a code would have to be capable of rewetting dry cells. MODFLOW is incapable of doing this properly at the present time. There are two rewetting subroutines available (McDonald, Harbaugh, Orr, and Ackerman 1991; Schenk and Poeter 1992). Neither subroutine is very robust, and neither works with MODFLOWP. Instead, a steady state model was constructed to approximate initial conditions at the site and the transient model used the heads, stream stages and flows from the steady state run to begin simulation of the spring runoff.

Another code problem was that only layer types 0 and 1 can be specified in MODFLOWP. Layer type 1 describes an unconfined aquifer, but can only be used for the top layer in a model. Layer type 0 can be used in the lower layers, but is a confined layer type. Therefore, the model had to be simulated as being unconfined in the top layer and confined in the bottom layers, in reality, the deeper layers should be described as convertible from confined to unconfined.

The problems above are compounded by the fact that recent data suggest the initial conceptual model was incorrect. The possibility of alternative conceptual models is discussed in the next section.

5. ALTERNATIVE CONCEPTUAL MODELS

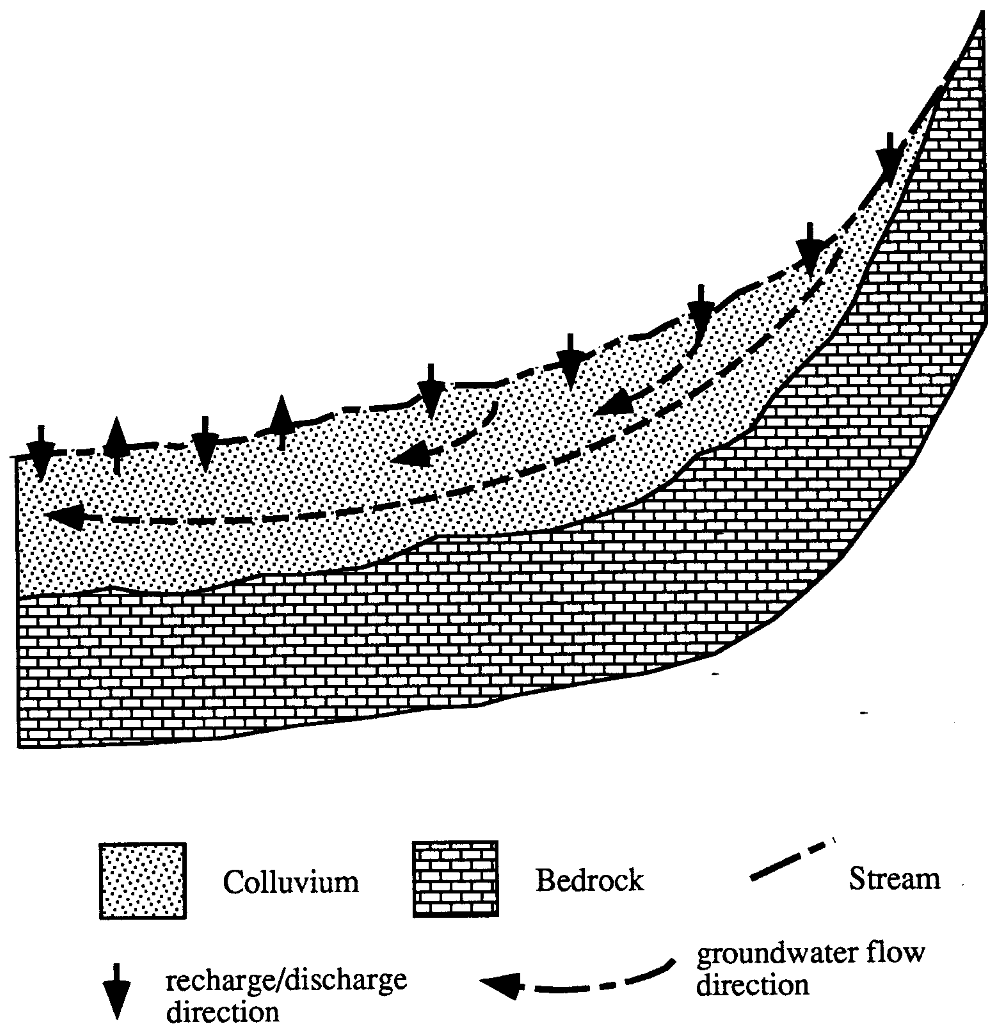
Geological and hydrogeological models are non-unique. Given the problems of data coverage encountered in this project that non-uniqueness is intensified. Recent data suggest that the conceptual model used in this project was flawed. The recent data includes two boreholes drilled in the area.

Figure 5.1 describes the conception of the area used in this project. Figure 5.1 and the two subsequent figures are cross sections along the stream. In this model, colluvium containing the aquifer is 10 to 25 feet thick. The underlying bedrock acts as an impermeable barrier. Recharge, solely from rainfall entering the area, feeds the stream and saturates the colluvium between the stream and the bedrock. No hydraulically significant layering occurs in the colluvium. All recharge to the area is from precipitation. Figure 5.1 only shows flow parallel to the stream but there is a component of flow perpendicular to the stream. The same is true of figures 5.2 and 5.3.

Alternative conceptual models are discussed below. The alternative models demonstrate that the original assumptions made about the geometry and parameters of the area for the model presented herein may be incorrect, and perhaps could be a significant cause of problems encountered in modeling the site.

The first of the alternative conceptual models is shown in figure 5.2. In this model the actual geometry of the system remains the same. The difference is that the bedrock is permeable and recharge can come from, or go to the bedrock.

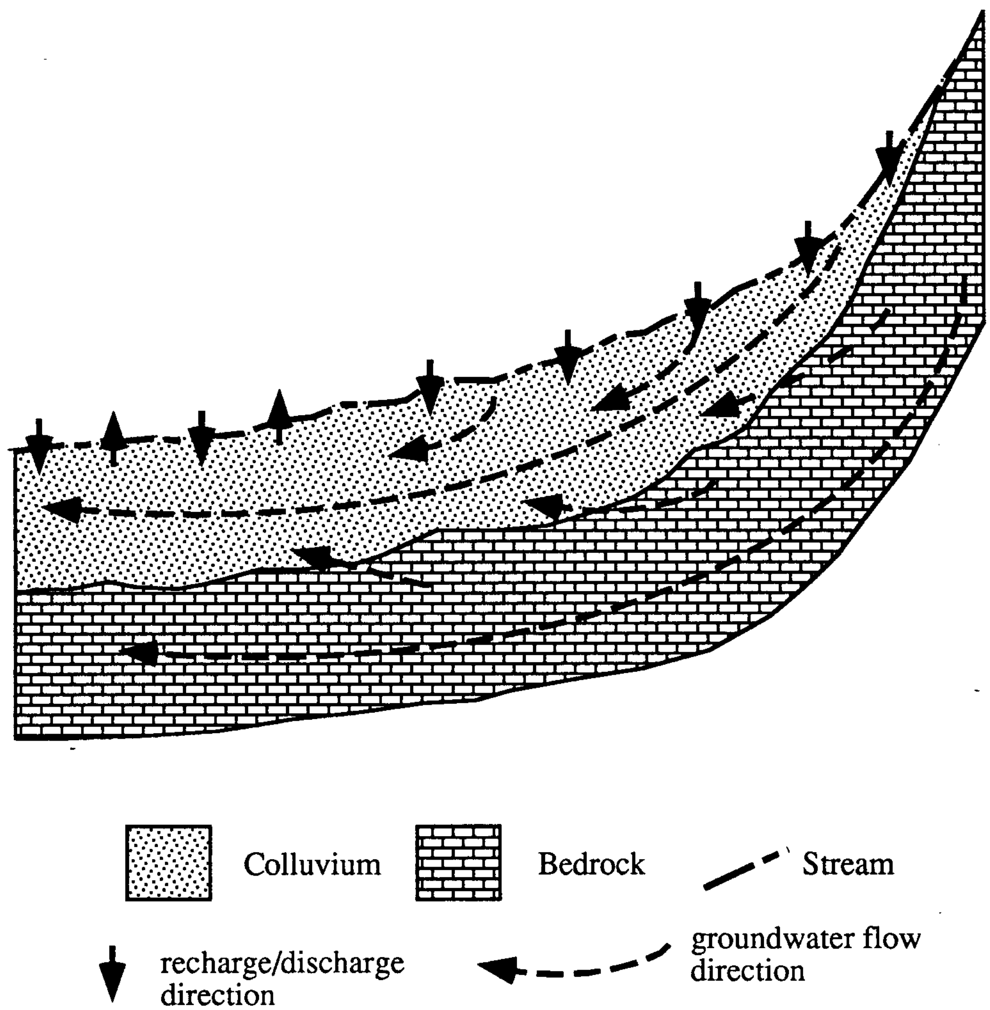
Another possibility is that layering exists in the colluvium, as presented in figure 5.3. Such layering may include a low permeability layer located a few feet below the surface. This layer perches water and the perched aquifer interacts with the stream. Bedrock formations in this conception are not significant in the model as they are not hydraulically connected to the perched aquifer. Field work is ongoing to better characterize the site and constrain the conceptual model.



This conceptual model was the one used in the modeling of this project. It assumes an impermeable boundary at the bedrock surface, thus all recharge originates from precipitation. Water flows down the mountain side through the colluvium, and when the aquifer becomes saturated and the water table reaches the ground surface, water from the aquifer discharges into the streambed causing flow through in the stream.

Conceptual Model #1

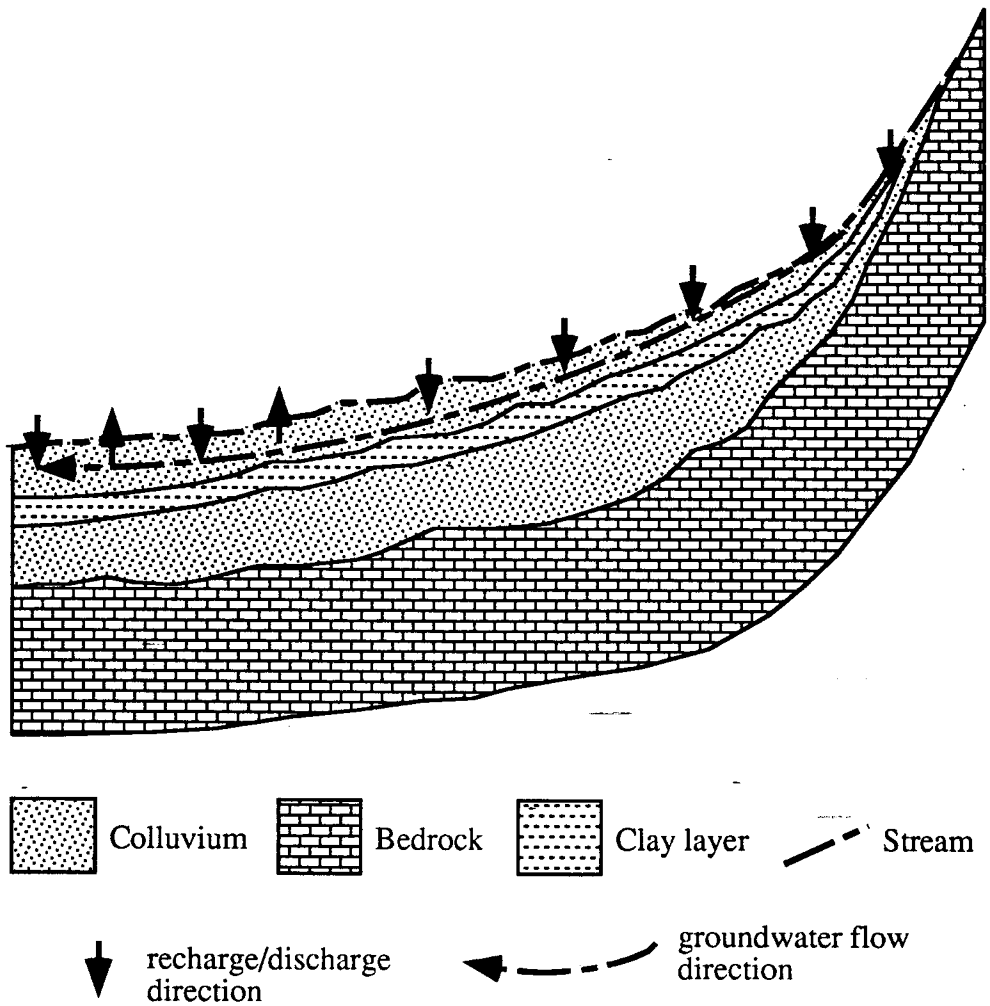
Figure 5.1



This conception of the area is the same as that of conceptual model #1, except that in this case the bedrock is not assumed to be impermeable so recharge can enter the colluvium from the bedrock (as shown), or recharge can leave the colluvium via the bedrock.

Conceptual Model # 2

Figure 5.2



This conceptual model of the area is similar to the previous two with the exception of the existance of layering within the colluvium. Here, there is an impermeable clay layer a few feet down in the colluvium, causing the recharge from precipitation to form a perched aquifer in the colluvium that feeds the stream when it becomes saturated to the ground surface.

Conceptual Model #3

Figure 5.3

6. DISCUSSION AND RECOMMENDATIONS FOR FURTHER WORK

There were many problems involved in the parameter estimation in this project. The difficulties fall into three main categories: limitations of MODFLOW and MODFLOWP; averaging of stream conditions to reduce computation time; and poor coverage of existing data.

Limitations of Codes

There were several limitations of the modeling codes that seriously affected the results of this study. The most important is the lack of a robust rewatering package for use with MODFLOW. Without such a package, an area similar to the one studied here cannot be simulated properly. One appropriate approach to modeling the site would be set up a model to run for several cycles, in this case several years. When the cycles become uniform from one to the next, the measurements would be compared to the calculated heads and flows. Another acceptable approach would be to start the area in a dry condition, and let the water table rise. Either of these approaches would allow a true transient calibration. Neither can be achieved with MODFLOW because grid cells cannot rewater.

MODFLOWP was found to be a useful tool in the calibration process. However, given the conditions at and knowledge of this site, the solver did not converge when the parameter starting values were far from an acceptable parameter set. Also, because data were lacking, very few parameters could be estimated.

Averaging of Stream Conditions

The nature of numerical models require discretization of the parameters describing groundwater flow in an area. This discretization smoothes and simplifies these parameters. Transverse to a stream, grid cell width affects the gradient between the aquifer and the stream as well as the representation of the curve of the potentiometric surface surrounding the stream. Laterally, large grid cell lengths can obscure, by averaging, the changes in the losing and gaining nature of a stream.

Poor Coverage of Data

The objective function being solved by MODFLOWP in this project was not well behaved. In other words, its minimum was difficult to find due to the nature of the objective function's surface. Therefore tight constraints had to be placed on vertical conductivity, and recharge was fixed to get the inverse model to converge. There is no valid support for these constraints based on the available data; they were used solely to force convergence. If there were accurate measurements of horizontal conductivity, vertical conductivity, streambed conductivity, or recharge, that parameter could be fixed or constrained and the model results would be closer to reality.

Heads and stream flows were measured over several months for the purposes of this project. The flow measurements, however, were not begun until well into the data collection period. The head data were only available directly under the stream, and to only a depth of 3 feet. Vertical head gradients close to the steam were available, but there is no field data regarding deeper hydraulic heads and gradients.

Hydraulic conductivity measurements were taken by Anderman (1992) and Anderman and Poeter (1993) with a variety of methods. The air permeameter measurements were the most reliable. However, they were suspect because they were outside the calibration range of the instrument. Also, they were only taken in the downstream portion of the area, and only to a depth of approximately two feet. The alluvium exceeds twenty feet in depth in some areas, and it is likely that the bulk hydraulic conductivity is different from that of the top two feet of the alluvium. It is not known whether that bulk value is higher or lower than that measured in the shallow materials. There may be very little silt and clay sized material at depth, implying a higher conductivity, or the weight of the overlying material could have compressed and packed the deeper alluvium, resulting in a lower bulk value of K.

The air permeameter was also used to measure the conductivity of the streambed. The parameter estimation routine never estimated a value much different (more than one order of magnitude) from that which was measured. However, the measurements were only taken in one location along the stream. The streambed materials vary from coarse gravel to fine organic materials. Hydraulic conductivity can range over six or seven orders of magnitude for unconsolidated materials (Freeze and Cherry, 1979). For this study, the different streambed materials were grouped into three categories: gravel, cobbles, and sand; sand, silt and clay; and clay and organic materials. The measurements had been taken in an area corresponding to the second category, sand, silt and clay. The first category was assumed to have a conductivity one order of magnitude higher, and the third, one order of magnitude lower. These ratios were not changed in the calibration process, but used as a multiplication array in the parameter estimation routine. It would have been useful to have estimated the conductivity of each category independently, but the amount and spatial distribution of data does not warrant such detail.

Precipitation measurements were assumed to be very accurate. It was assumed that recharge was 10% of the measured precipitation. However there were no measurements of recharge. This area is semi-arid so it is possible that the net recharge is less than 10% of the precipitation. Precipitation may not be the only form of recharge. The stream colluvium may provide a groundwater drain the side of a mountain, and could be a discharge area. It has been assumed that the bedrock is impermeable, but it is possible that it is not, and that water is entering the area from the bedrock. Much of that water could be evapotranspired. Ideally recharge should be estimated by MODFLOWP. It was found that with the lack of data, apparently unrealistic parameter estimates were obtained by the steady state runs, and convergence could not be achieved in the transient runs. If the other parameters could be better constrained and more head and flow data were available, then MODFLOWP would probably be able to estimate recharge independently.

The data coverage problems contributed to the possibility that the conceptual model used was inaccurate. More must be known about the area to better constrain the conceptual model.

Sensitivity Study

MODFLOWP allows the user to test the sensitivity of a model to data in specified locations. Potential data locations can be included in a model to test the usefulness of the collection of head or flow data at those locations. The values assigned to these points is irrelevant, the model can calculate the sensitivity of these data points independent from their given values. The larger the absolute value of the sensitivity, the more sensitive the model is to that data point. The sensitivity is calculated for each data point relative to each parameter being estimated.

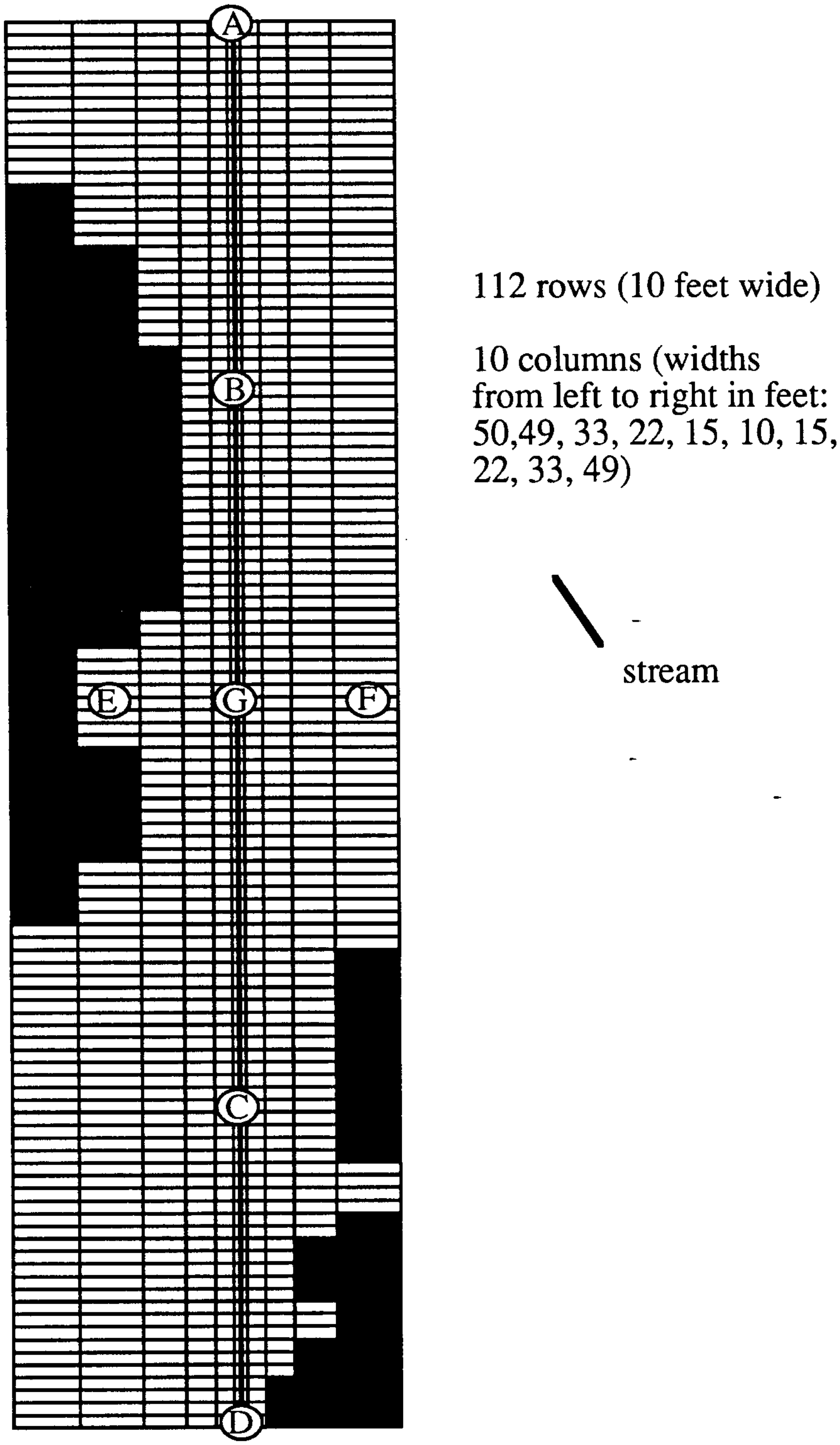
This procedure was followed to test the sensitivity of possible borehole locations to the model. Figure 6.1 shows the locations that were tested. Each location was tested for wells screened in the 3rd and 4th layers (there are already many shallow piezometers, deeper ones are needed), with measurements at various time steps. The sensitivities at the various time steps for each location and depth were averaged and are shown in table 1. The model is most sensitive to well location G for each of the parameters. This is the well under the stream itself at the center of the model. E and F are offset from the stream, and the sensitivities are good, but not as high as for several of the other wells. Of the rest of the well locations, B and C are the best. Results indicate insensitivity to data at A and D.

well and depth	T	KV	KST	RCH
A @ 4ft	-1.67E-02	-2.56E-04	-8.62E-07	-2.33E-06
B @ 4ft	6.44E-01	-6.65E-01	-2.22E-03	-5.85E-03
C @ 4ft	9.75E-01	-9.89E-01	-3.15E-03	-8.28E-03
D @ 4ft	2.19E-02	-2.27E-04	-9.76E-07	-2.61E-06
A @ 3ft	-7.97E-03	3.16E-04	-6.31E-06	-1.69E-05
B @ 3ft	-1.95E+00	2.12E+00	-4.18E-02	-1.03E-01
C @ 3ft	-2.75E+00	3.06E+00	-5.59E-02	-1.34E-01
D @ 3ft	1.38E-02	5.44E-04	-1.35E-05	-3.35E-05
E @ 4ft	8.92E-01	-9.09E-01	-2.93E-03	-7.71E-03
F @ 4ft	9.10E-01	-9.28E-01	-2.98E-03	-7.83E-03
G @ 4ft	5.49E+00	-5.38E+00	-2.79E-01	2.31E-01

Table 6.1

Sensitivity values of T, KV, KST, RCH, at well locations A through G

According to the results presented in table 6.1, if funds were available for only one borehole, it should be placed in the middle of the area. However locations A and D are needed to determine boundary condition values and estimate conductance. Since they are located in boundary cells with fixed heads, the sensitivity values are, of course, very low. However, boundary conditions have an enormous effect on mathematical models, so locations A and D must be considered to be the most important locations for new data.



Well Locations Tested With Sensitivity Analysis

Figure 6.1

It would have been helpful to this project if measurements of conductivity and recharge were available. It would be extremely helpful to the modeling of this area if there was an accurate, bulk estimate of hydraulic conductivity. This could be accomplished with at least two wells and a pumping test. If this was done, K could be better constrained, and more leeway could be given to the other parameters that are less well known.

Future Work

With this in mind, it is recommended that wells be drilled at locations A and D, or as close as accessibility allows. The wells should be drilled to bedrock to verify the geophysical interpretations. This has been done recently. Hydraulic tests should be conducted in these holes to measure bulk hydraulic conductivity and storage coefficient. If the layering is such that large differences are expected in the K values for each unit, packer tests could be done on the various units to determine their individual K's. Three piezometers should then be installed, at approximately 2 feet, 4 to 5 feet, and 10 to 12 feet in each of the three wells at each location. The proposed depths for piezometers can be altered depending upon the layering observed during drilling. Three piezometers will allow calculation of vertical head gradients.

More measurements of streambed conductivity are needed. Infiltration tests could be used to take more measurements at areas along the streambed that have different material compositions. Measurements should be taken at, at least, two or three locations that correspond to each of the three broad categories of sediments. A better estimate of the ratios of hydraulic conductivity values between these groups of materials would be useful.

The modeling software should be modified to improve the accuracy of the simulations in this area. First, an algorithm for rewetting cells should be incorporated to allow proper setup of the transient model. Second, MODFLOWP should be modified to estimate parameters for convertible layers.

There is much research in the field of groundwater modeling that needs to be done to properly simulate stream/aquifer interaction. Perhaps even more important than advances in the coding of the modeling programs is improvements in data collection. Hydrogeologists need more accurate, and lower cost ways of measuring aquifer parameters. There are many methods that look promising, particularly in the field of geophysics. Future work in both the modeling and the data collection will no doubt allow much more accurate simulation of surface water groundwater interaction.

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APPENDIX A

Head and Flow Data

Surface	Stream	Elevation	in feet						Stream
	Flow	Farthest		Original				Packed	Flow
Date	ft^3/sec.	0 ft	25 ft	25 ft	75 ft	105 ft	145 ft	180 ft	ft^3/sec.
2/25/92	n/a	5888.55	5889.18	5889.12	5890.94	5892.29	5894.08	5895.81	n/a
3/5/92	n/a	5888.55	5889.12	5889.13	5890.96	5892.30	5894.11	5895.80	n/a
3/9/92	n/a	5888.60	5889.19	5889.19	5891.05	5892.38	5894.24	5895.99	n/a
3/10/92	n/a	5888.59	5889.17	5889.18	5891.04	5892.37	5894.21	5895.96	n/a
3/12/92	n/a	5888.62	5889.20	5889.20	5891.09	5892.38	5894.25	5896.00	n/a
3/27/92	n/a	5888.76	5889.34	5889.33	5891.26	5892.50	5894.34	5896.16	n/a
3/30/92	n/a	5888.78	5889.33	5889.33	5891.29	5892.53	5894.42	5896.19	n/a
3/31/92	n/a	5888.78	5889.35	5889.34	5891.31	5892.52	5894.44	5896.21	n/a
4/1/92	n/a	5888.74	5889.31	5889.32	5891.29	5892.50	5894.42	5896.15	n/a
4/2/92	n/a	5888.75	5889.29	5889.31	5891.25	5892.49	5894.41	5896.15	n/a
4/3/92	n/a	5888.73	5889.29	5889.28	5891.24	5892.50	5894.40	5896.14	n/a
4/4/92	n/a	5888.74	5889.28	5889.28	5891.23	5892.49	5894.35	5896.13	n/a
4/5/92	n/a	5888.72	5889.26	5889.27	5891.22	5892.47	5894.31	5896.15	n/a
4/6/92	n/a	5888.72	5889.26	5889.26	5891.19	5892.48	5894.33	5896.10	n/a
4/7/92	n/a	5888.70	5889.24	5889.25	5891.17	5892.46	5894.30	5896.10	n/a
4/9/92	n/a	5888.69	5889.23	5889.23	5891.15	5892.43	5894.24	5896.10	n/a
4/13/92	n/a	5888.63	5889.19	5889.19	5891.10	5892.41	5894.25	5896.05	n/a
4/16/92	n/a	5888.63	5889.19	5889.19	5891.09	5892.40	5894.24	5896.02	n/a
4/20/92	n/a	5888.58	5889.14	5889.15	5891.04	5892.36	5894.21	5895.95	n/a
4/22/92	0.1487	5888.57	5889.14	5889.13	5891.01	5892.35	5894.20	5895.93	n/a
4/24/92	0.1269	5888.54	5889.10	5889.10	5890.98	5892.32	5894.17	5895.89	n/a
4/29/92	0.0715	5888.52	5889.08	5889.08	5890.94	5892.30	5894.12	5895.82	n/a
5/4/92	0.0712	5888.52	5889.08	5889.09	5890.93	5892.29	5894.11	5895.81	0.0000
5/6/92	0.0697	5888.52	5889.07	5889.07	5890.92	5892.28	5894.10	5895.80	0.0000
5/8/92	0.0627	5888.53	5889.07	5889.07	5890.92	5892.27	5894.10	5895.80	0.0000
5/18/92	0.0523	5888.54	5889.07	5889.07	5890.91	5892.27	5894.07	5895.78	0.0000
5/21/92	0.0548	5888.59	5889.13	5889.10	5890.90	5892.30	5894.86	5895.81	0.0000
5/22/92	0.0554	5888.56	5889.11	5889.10	5890.93	5892.30	5894.08	5895.80	0.0000
5/26/92	0.0436	5888.53	5889.08	5889.09	5890.91	5892.26	5894.03	5895.77	0.0000
5/27/92	0.0436	5888.57	5889.13	5889.12	5890.94	5892.30	5894.07	5895.79	0.0000
5/27/92	0.0436	5888.58	5889.13	5889.12	5890.95	5892.30	5894.07	5895.79	0.0000
5/28/92	0.0436	5888.58	5889.12	5889.12	5890.94	5892.31	5894.07	5895.79	0.0000
5/28/92	0.0439	5888.57	5889.10	5889.09	5890.92	5892.28	5894.06	5895.79	0.0000
5/29/92	0.0415	5888.58	5889.13	5889.13	5890.93	5892.31	5894.07	5895.78	0.0000
5/30/92	0.0404	5888.58	5889.12	5889.14	5890.92	5892.27	5894.07	5895.79	0.0000
6/1/92	0.0470	5888.60	5889.15	5889.14	5890.95	5892.31	5894.07	5895.79	0.0000
6/1/92	0.0529	5888.60	5889.15	5889.15	5890.96	5892.32	5894.09	5895.80	0.0000
6/2/92	0.0470	5888.60	5889.15	5889.15	5890.95	5892.32	5894.08	5895.80	0.0000
6/2/92	0.0459	5888.57	5889.15	5889.15	5890.95	5892.32	5894.08	5895.80	0.0000
6/3/92	0.0470	5888.58	5889.15	5889.14	5890.94	5892.31	5894.06	5895.80	0.0000
6/4/92	0.0447	5888.59	5889.16	5889.16	5890.94	5892.30	5894.05	5895.81	0.0000
6/4/92	0.0402	5888.59	5889.14	5889.16	5890.95	5892.31	5894.07	5895.83	0.0000
6/7/92	0.0403	5888.58	5889.17	5889.18	5890.95	5892.32	5894.06	5895.83	0.0000
6/15/92	0.0379	5888.63	5889.22	5889.22	5890.96	5892.33	5893.75	5895.80	0.0000
6/19/92	0.0326	5888.61	5889.24	5889.21	5890.98	5892.33	5893.75	5895.80	0.0000
6/22/92	0.0259	5888.57	5889.23	5889.23	5890.99	5892.35	5893.75	5895.80	0.0000
6/26/92	0.0178	5888.55	5889.18	5889.20	5890.99	5892.35	5893.75	5895.80	0.0000
6/29/92	0.0111	5888.55	5889.17	5889.17	5890.96	5892.41	5893.75	5895.80	0.0000
7/8/92	0.0013	5888.55	5889.15	5889.15	5890.92	5892.20	5893.75	5895.77	0.0000
7/13/92	0.0000	5888.55	5889.12	5889.12	5890.92	5892.20	5893.75	5895.77	0.0000
7/24/92	0.0000	5888.55	5888.92	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
7/27/92	0.0000	5888.55	5888.92	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
7/31/92	0.0000	5888.55	5888.91	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
8/3/92	0.0000	5888.55	5888.91	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
8/7/92	0.0000	5888.55	5888.91	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
8/13/92	0.0000	5888.55	5888.85	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000
8/20/92	0.0000	5888.55	5888.85	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000
8/25/92	0.0000	5888.55	5888.91	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000
8/26/92	0.0000	5888.55	5888.85	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000
9/3/92	0.0000	5888.55	5888.92	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000

Surface								
					Stream			Stream
Date	330	480	630	780	Flow	930	1080	Flow
2/25/92	5905.09	5912.40	5923.01	5932.12	n/a	5941.95	5952.24	n/a
3/5/92	5905.09	5912.42	5923.08	5932.43	n/a	5942.17	5952.45	n/a
3/9/92	5905.37	5912.62	5923.27	5932.49	n/a	5942.32	5952.50	n/a
3/10/92	5905.35	5912.58	5923.24	5932.47	n/a	5942.30	5952.49	n/a
3/12/92	5905.38	5912.62	5923.29	5932.47	n/a	5942.32	5952.52	n/a
3/27/92	5905.52	5912.97	5923.53	5932.66	n/a	5942.45	5952.62	n/a
3/30/92	5905.49	5913.00	5923.54	5932.36	n/a	5942.44	5952.62	n/a
3/31/92	5905.51	5913.03	5923.59	5932.36	n/a	5942.45	5952.64	n/a
4/1/92	5905.49	5912.97	5923.54	5932.36	n/a	5942.44	5952.62	n/a
4/2/92	5905.48	5912.95	5923.52	5932.36	n/a	5942.42	5952.60	n/a
4/3/92	5905.47	5912.95	5923.49	5932.36	n/a	5942.42	5952.62	n/a
4/4/92	5905.48	5912.93	5923.48	5932.36	n/a	5942.41	5952.62	n/a
4/5/92	5905.47	5912.92	5923.48	5932.36	n/a	5942.39	5952.57	n/a
4/6/92	5905.46	5912.90	5923.46	5932.36	n/a	5942.37	5952.60	n/a
4/7/92	5905.45	5912.88	5923.44	5932.36	n/a	5942.35	5952.60	n/a
4/9/92	5905.44	5912.85	5923.42	5932.36	n/a	5942.33	5952.59	n/a
4/13/92	5905.41	5912.78	5923.37	5932.36	n/a	5942.26	5952.55	n/a
4/16/92	5905.40	5912.79	5923.34	5932.36	n/a	5942.28	5952.55	n/a
4/20/92	5905.34	5912.71	5923.25	5932.36	n/a	5942.18	5952.49	n/a
4/22/92	5905.33	5912.68	5923.23	5932.36	n/a	5942.15	5952.50	0.10
4/24/92	5905.28	5912.62	5923.20	5932.36	n/a	5942.09	5952.46	0.08
4/29/92	5905.16	5912.54	5923.14	5932.36	n/a	5942.01	5952.38	0.01
5/4/92	5905.13	5912.50	5923.12	5932.36	0.0165	5942.00	5952.36	0.00
5/6/92	5905.13	5912.43	5923.07	5932.36	0.0243	5941.97	5952.32	0.00
5/8/92	5905.13	5912.40	5923.03	5932.36	0.0029	5941.95	5952.31	0.00
5/18/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
5/21/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	n/a
5/22/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.91	5952.27	0.00
5/26/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.88	5952.27	0.00
5/27/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.98	5952.39	0.01
5/27/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.98	5952.39	0.01
5/28/92	5905.13	5912.40	5923.03	5932.36	0.0088	5942.02	5952.41	0.03
5/28/92	5905.13	5912.40	5923.03	5932.36	0.0018	5941.97	5952.36	0.01
5/29/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.94	5952.33	0.00
5/30/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.86	5952.32	0.00
6/1/92	5905.13	5912.40	5923.03	5932.36	0.0000	5942.10	5952.47	0.00
6/1/92	5905.13	5912.40	5923.03	5932.36	0.0464	5942.08	5952.47	0.08
6/2/92	5905.13	5912.40	5923.03	5932.36	0.0301	5942.03	5952.40	0.04
6/2/92	5905.13	5912.40	5923.03	5932.36	0.0047	5941.98	5952.35	0.01
6/3/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.97	5952.34	0.00
6/4/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.97	5952.34	0.00
6/4/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.95	5952.27	0.00
6/7/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.90	5952.27	0.00
6/15/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
6/19/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
6/22/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
6/26/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
6/29/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
7/8/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
7/13/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
7/24/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
7/27/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
7/31/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
8/3/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
8/7/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
8/13/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
8/20/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
8/25/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
8/26/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00
9/3/92	5905.13	5912.40	5923.03	5932.36	0.0000	5941.83	5952.27	0.00

1 ft piez.									
	Stream	Farthest		Original				Packed	Stream
Date	Flow	0	25	25	75	105	145	180	Flow
2/25/92	n/a	5887.99	5889.02	5889.04	5891.16	5892.57	5894.18	5895.17	n/a
3/5/92	n/a	5887.98	5889.03	5889.04	5891.18	5892.64	5894.33	5895.50	n/a
3/9/92	n/a	5888.08	5889.07	5889.09	5891.25	5892.74	5894.68	5896.09	n/a
3/10/92	n/a	5888.09	5889.08	5889.09	5891.26	5892.76	5894.69	5896.11	n/a
3/12/92	n/a	5888.14	5889.12	5889.13	5891.29	5892.82	5894.79	5896.21	n/a
3/27/92	n/a	5888.25	5889.22	5889.22	5891.41	5892.90	5894.99	5896.59	n/a
3/30/92	n/a	5888.21	5889.24	5889.26	5891.45	5892.93	5895.02	5896.58	n/a
3/31/92	n/a	5888.22	5889.26	5889.29	5891.46	5892.94	5895.02	5896.46	n/a
4/1/92	n/a	5888.34	5889.23	5889.27	5891.43	5892.92	5895.02	5896.45	n/a
4/2/92	n/a	5888.21	5889.21	5889.23	5891.37	5892.91	5895.01	5896.48	n/a
4/3/92	n/a	5888.21	5889.21	5889.23	5891.41	5892.92	5895.00	5896.45	n/a
4/4/92	n/a	5888.20	5889.21	5889.27	5891.40	5892.92	5894.99	5896.47	n/a
4/5/92	n/a	5888.18	5889.23	5889.23	5891.39	5892.91	5895.11	5896.67	n/a
4/6/92	n/a	5888.16	5889.20	5889.26	5891.36	5892.91	5894.98	5896.53	n/a
4/7/92	n/a	5888.14	5889.19	5889.20	5891.36	5892.91	5895.01	5896.48	n/a
4/9/92	n/a	5888.12	5889.17	5889.19	5891.34	5892.88	5894.95	5896.48	n/a
4/13/92	n/a	5888.08	5889.14	5889.16	5891.31	5892.88	5894.93	5896.52	n/a
4/16/92	n/a	5888.11	5889.15	5889.17	5891.31	5892.86	5894.91	5896.49	n/a
4/20/92	n/a	5888.04	5889.10	5889.15	5891.26	5892.86	5894.91	5896.37	n/a
4/22/92	0.1487	5888.02	5889.10	5889.13	5891.26	5892.87	5894.87	5896.42	n/a
4/24/92	0.1269	5888.02	5889.07	5889.12	5891.24	5892.78	5894.83	5896.36	n/a
4/29/92	0.0715	5887.95	5889.04	5889.05	5891.22	5892.76	5894.82	5896.30	n/a
5/4/92	0.0712	5887.94	5889.03	5889.12	5891.21	5892.83	5894.83	5896.26	0.0000
5/6/92	0.0697	5887.93	5889.02	5889.06	5891.20	5892.78	5894.91	5896.29	0.0000
5/8/92	0.0627	5887.93	5889.03	5889.08	5891.23	5892.76	5894.83	5896.24	0.0000
5/18/92	0.0523	5887.92	5889.00	5889.03	5891.23	5892.73	5894.76	5896.07	0.0000
5/21/92	0.0548	5887.98	5889.06	5889.07	5891.25	5892.66	5894.69	5896.04	0.0000
5/22/92	0.0554	5887.96	5889.05	5889.03	5891.26	5892.66	5894.65	5896.00	0.0000
5/26/92	0.0436	5887.97	5889.02	5889.05	5891.26	5892.63	5894.52	5895.83	0.0000
5/27/92	0.0436	5888.00	5889.09	5889.11	5891.32	5892.66	5894.55	5895.85	0.0000
5/27/92	0.0436	5887.98	5889.09	5889.11	5891.32	5892.66	5894.54	5895.85	0.0000
5/28/92	0.0436	5887.96	5889.08	5889.10	5891.29	5892.65	5894.52	5895.82	0.0000
5/28/92	0.0439	5888.00	5889.06	5889.08	5891.31	5892.64	5894.50	5895.80	0.0000
5/29/92	0.0415	5887.95	5889.08	5889.09	5891.31	5892.62	5894.48	5895.74	0.0000
5/30/92	0.0404	5887.92	5889.06	5889.10	5891.29	5892.61	5894.45	5895.75	0.0000
6/1/92	0.0470	5888.06	5889.09	5889.13	5891.26	5892.57	5894.39	5895.79	0.0000
6/1/92	0.0529	5888.02	5889.11	5889.13	5891.29	5892.60	5894.39	5895.89	0.0000
6/2/92	0.0470	5888.00	5889.10	5889.12	5891.29	5892.60	5894.37	5895.86	0.0000
6/2/92	0.0459	5888.01	5889.09	5889.11	5891.29	5892.60	5894.38	5895.86	0.0000
6/3/92	0.0470	5888.01	5889.08	5889.11	5891.27	5892.58	5894.35	5895.83	0.0000
6/4/92	0.0447	5888.01	5889.10	5889.12	5891.26	5892.56	5894.34	5895.81	0.0000
6/4/92	0.0402	5888.00	5889.08	5889.11	5891.26	5892.55	5894.32	5895.81	0.0000
6/7/92	0.0403	5888.02	5889.09	5889.12	5891.25	5892.56	5894.31	5895.74	0.0000
6/15/92	0.0379	5887.84	5889.11	5889.14	5891.20	5892.56	full	5895.77	0.0000
6/19/92	0.0326	5887.84	5889.13	5889.15	5891.19	5892.52	full	5895.32	0.0000
6/22/92	0.0259	5887.80	5889.12	5889.13	5891.21	5892.50	full	5894.97	0.0000
6/26/92	0.0178	5887.82	5889.13	5889.13	5891.27	5892.50	full	dry	0.0000
6/29/92	0.0111	5887.79	5889.08	5889.09	5891.16	5892.55	full	dry	0.0000
7/8/92	0.0013	5887.69	5889.03	5889.19	5891.09	5892.05	full	dry	0.0000
7/13/92	0.0000	5887.66	5889.00	5889.06	5891.02	5891.75	full	dry	0.0000
7/24/92	0.0000	dry	5888.58	5888.55	5890.54	dry	full	dry	0.0000
7/27/92	0.0000	dry	5888.36	5888.29	5890.30	dry	full	dry	0.0000
7/31/92	0.0000	dry	dry	5888.08	5890.20	dry	full	dry	0.0000
8/3/92	0.0000	dry	dry	5888.01	dry	dry	full	dry	0.0000
8/7/92	0.0000	dry	dry	dry	dry	dry	full	dry	0.0000
8/13/92	0.0000	dry	dry	dry	dry	dry	full	dry	0.0000
8/20/92	0.0000	dry	dry	dry	dry	dry	full	dry	0.0000
8/25/92	0.0000	dry	dry	dry	dry	dry	full	dry	0.0000
8/26/92	0.0000	dry	dry	dry	dry	dry	full	dry	
9/3/92	0.0000	dry	dry	dry	dry	dry	full	dry	

Surface									
	Stream	Farthest		Original				Packed	Stream
Date	Flow	0	25	25	75	105	145	180	Flow
2/25/92	n/a	5888.55	5889.18	5889.12	5890.94	5892.29	5894.08	5895.81	n/a
3/5/92	n/a	5888.55	5889.12	5889.13	5890.96	5892.30	5894.11	5895.80	n/a
3/9/92	n/a	5888.60	5889.19	5889.19	5891.05	5892.38	5894.24	5895.99	n/a
3/10/92	n/a	5888.59	5889.17	5889.18	5891.04	5892.37	5894.21	5895.96	n/a
3/12/92	n/a	5888.62	5889.20	5889.20	5891.09	5892.38	5894.25	5896.00	n/a
3/27/92	n/a	5888.76	5889.34	5889.33	5891.26	5892.50	5894.34	5896.16	n/a
3/30/92	n/a	5888.78	5889.33	5889.33	5891.29	5892.53	5894.42	5896.19	n/a
3/31/92	n/a	5888.78	5889.35	5889.34	5891.31	5892.52	5894.44	5896.21	n/a
4/1/92	n/a	5888.74	5889.31	5889.32	5891.29	5892.50	5894.42	5896.15	n/a
4/2/92	n/a	5888.75	5889.29	5889.31	5891.25	5892.49	5894.41	5896.15	n/a
4/3/92	n/a	5888.73	5889.29	5889.28	5891.24	5892.50	5894.40	5896.14	n/a
4/4/92	n/a	5888.74	5889.28	5889.28	5891.23	5892.49	5894.35	5896.13	n/a
4/5/92	n/a	5888.72	5889.26	5889.27	5891.22	5892.47	5894.31	5896.15	n/a
4/6/92	n/a	5888.72	5889.26	5889.26	5891.19	5892.48	5894.33	5896.10	n/a
4/7/92	n/a	5888.70	5889.24	5889.25	5891.17	5892.46	5894.30	5896.10	n/a
4/9/92	n/a	5888.69	5889.23	5889.23	5891.15	5892.43	5894.24	5896.10	n/a
4/13/92	n/a	5888.63	5889.19	5889.19	5891.10	5892.41	5894.25	5896.05	n/a
4/16/92	n/a	5888.63	5889.19	5889.19	5891.09	5892.40	5894.24	5896.02	n/a
4/20/92	n/a	5888.58	5889.14	5889.15	5891.04	5892.36	5894.21	5895.95	n/a
4/22/92	0.1487	5888.57	5889.14	5889.13	5891.01	5892.35	5894.20	5895.93	n/a
4/24/92	0.1269	5888.54	5889.10	5889.10	5890.98	5892.32	5894.17	5895.89	n/a
4/29/92	0.0715	5888.52	5889.08	5889.08	5890.94	5892.30	5894.12	5895.82	n/a
5/4/92	0.0712	5888.52	5889.08	5889.09	5890.93	5892.29	5894.11	5895.81	0.0000
5/6/92	0.0697	5888.52	5889.07	5889.07	5890.92	5892.28	5894.10	5895.80	0.0000
5/8/92	0.0627	5888.53	5889.07	5889.07	5890.92	5892.27	5894.10	5895.80	0.0000
5/18/92	0.0523	5888.54	5889.07	5889.07	5890.91	5892.27	5894.07	5895.78	0.0000
5/21/92	0.0548	5888.59	5889.13	5889.10	5890.90	5892.30	5894.86	5895.81	0.0000
5/22/92	0.0554	5888.56	5889.11	5889.10	5890.93	5892.30	5894.08	5895.80	0.0000
5/26/92	0.0436	5888.53	5889.08	5889.09	5890.91	5892.26	5894.03	5895.77	0.0000
5/27/92	0.0436	5888.57	5889.13	5889.12	5890.94	5892.30	5894.07	5895.79	0.0000
5/27/92	0.0436	5888.58	5889.13	5889.12	5890.95	5892.30	5894.07	5895.79	0.0000
5/28/92	0.0436	5888.58	5889.12	5889.12	5890.94	5892.31	5894.07	5895.79	0.0000
5/28/92	0.0439	5888.57	5889.10	5889.09	5890.92	5892.28	5894.06	5895.79	0.0000
5/29/92	0.0415	5888.58	5889.13	5889.13	5890.93	5892.31	5894.07	5895.78	0.0000
5/30/92	0.0404	5888.58	5889.12	5889.14	5890.92	5892.27	5894.07	5895.79	0.0000
6/1/92	0.0470	5888.60	5889.15	5889.14	5890.95	5892.31	5894.07	5895.79	0.0000
6/1/92	0.0529	5888.60	5889.15	5889.15	5890.96	5892.32	5894.09	5895.80	0.0000
6/2/92	0.0470	5888.60	5889.15	5889.15	5890.95	5892.32	5894.08	5895.80	0.0000
6/2/92	0.0459	5888.57	5889.15	5889.15	5890.95	5892.32	5894.08	5895.80	0.0000
6/3/92	0.0470	5888.58	5889.15	5889.14	5890.94	5892.31	5894.06	5895.80	0.0000
6/4/92	0.0447	5888.59	5889.16	5889.16	5890.94	5892.30	5894.05	5895.81	0.0000
6/4/92	0.0402	5888.59	5889.14	5889.16	5890.95	5892.31	5894.07	5895.83	0.0000
6/7/92	0.0403	5888.58	5889.17	5889.18	5890.95	5892.32	5894.06	5895.83	0.0000
6/15/92	0.0379	5888.63	5889.22	5889.22	5890.96	5892.33	5893.75	5895.80	0.0000
6/19/92	0.0326	5888.61	5889.24	5889.21	5890.98	5892.33	5893.75	5895.80	0.0000
6/22/92	0.0259	5888.57	5889.23	5889.23	5890.99	5892.35	5893.75	5895.80	0.0000
6/26/92	0.0178	5888.55	5889.18	5889.20	5890.99	5892.35	5893.75	5895.80	0.0000
6/29/92	0.0111	5888.55	5889.17	5889.17	5890.96	5892.41	5893.75	5895.80	0.0000
7/8/92	0.0013	5888.55	5889.15	5889.15	5890.92	5892.20	5893.75	5895.77	0.0000
7/13/92	0.0000	5888.55	5889.12	5889.12	5890.92	5892.20	5893.75	5895.77	0.0000
7/24/92	0.0000	5888.55	5888.92	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
7/27/92	0.0000	5888.55	5888.92	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
7/31/92	0.0000	5888.55	5888.91	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
8/3/92	0.0000	5888.55	5888.91	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
8/7/92	0.0000	5888.55	5888.91	5889.02	5890.84	5892.20	5893.75	5895.86	0.0000
8/13/92	0.0000	5888.55	5888.85	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000
8/20/92	0.0000	5888.55	5888.85	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000
8/25/92	0.0000	5888.55	5888.91	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000
8/26/92	0.0000	5888.55	5888.85	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000
9/3/92	0.0000	5888.55	5888.92	5889.02	5890.84	5892.20	5893.75	5895.77	0.0000

2 ft piez.								
					Stream			Stream
Date	330	480	630	780	Flow	930	1080	Flow
2/25/92	dry	dry	dry	dry	n/a	5941.59	5951.77	n/a
3/5/92	dry	dry	5922.77	5932.27	n/a	5942.27	5952.59	n/a
3/9/92	5904.66	5912.09	5923.01	5932.07	n/a	5942.42	5952.78	n/a
3/10/92	5904.73	5912.22	5923.08	5931.98	n/a	5942.43	5952.81	n/a
3/12/92	5904.88	5912.35	5923.19	5931.82	n/a	5942.46	5952.85	n/a
3/27/92	5905.27	5912.54	5923.21	dry	n/a	5942.50	5953.12	n/a
3/30/92	5904.55	5912.46	5923.09	dry	n/a	5942.55	5953.19	n/a
3/31/92	5904.48	5912.54	5923.00	dry	n/a	5942.57	5953.19	n/a
4/1/92	5904.36	5912.34	5922.91	dry	n/a	5942.54	5953.16	n/a
4/2/92	5904.31	5912.31	5922.84	dry	n/a	5942.53	5953.15	n/a
4/3/92	5904.31	5912.33	5922.81	dry	n/a	5942.52	5953.15	n/a
4/4/92	5904.29	5912.24	5922.74	dry	n/a	5942.52	5953.04	n/a
4/5/92	5904.23	5912.48	5922.67	dry	n/a	5942.50	5953.15	n/a
4/6/92	5904.25	5912.17	5922.65	dry	n/a	5942.50	5953.14	n/a
4/7/92	5904.22	5912.15	5922.57	dry	n/a	5942.47	5953.13	n/a
4/9/92	5904.32	5912.18	5922.46	dry	n/a	5942.46	5953.12	n/a
4/13/92	5904.39	5911.99	5922.28	dry	n/a	5942.42	5953.06	n/a
4/16/92	5904.25	5911.90	5922.17	dry	n/a	5942.42	5953.05	n/a
4/20/92	dry	5911.75	dry	dry	n/a	5942.36	5952.96	n/a
4/22/92	dry	5911.67	dry	dry	n/a	5942.33	5952.95	0.10
4/24/92	dry	5911.58	dry	dry	n/a	5942.31	5952.88	0.08
4/29/92	dry	dry	dry	dry	n/a	5942.25	5952.77	0.01
5/4/92	dry	dry	dry	5931.21	0.0165	5942.15	5952.66	0.00
5/6/92	dry	dry	dry	dry	0.0243	5942.11	5952.58	0.00
5/8/92	dry	dry	dry	dry	0.0029	5942.06	5952.49	0.00
5/18/92	dry	dry	dry	dry	0.0000	5941.10	5951.71	0.00
5/21/92	dry	dry	dry	dry	0.0000	dry	dry	n/a
5/22/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
5/26/92	dry	dry	dry	dry	0.0000	dry	5952.22	0.00
5/27/92	dry	dry	dry	dry	0.0000	5941.36	5952.39	0.01
5/27/92	dry	dry	dry	dry	0.0000	5941.43	5952.42	0.01
5/28/92	dry	dry	dry	5931.96	0.0088	5941.62	5952.49	0.03
5/28/92	dry	dry	dry	5931.47	0.0018	5941.63	5952.49	0.01
5/29/92	dry	dry	dry	dry	0.0000	5941.69	5952.51	0.00
5/30/92	dry	dry	dry	dry	0.0000	5941.52	5952.44	0.00
6/1/92	dry	dry	dry	5932.02	0.0000	5941.90	5952.58	0.00
6/1/92	dry	dry	dry	5932.03	0.0464	5941.95	5952.64	0.08
6/2/92	dry	dry	dry	5932.04	0.0301	5941.96	5952.67	0.04
6/2/92	dry	dry	dry	dry	0.0047	5941.95	5952.66	0.01
6/3/92	dry	dry	dry	dry	0.0000	5941.94	5952.59	0.00
6/4/92	dry	dry	dry	dry	0.0000	5941.94	5952.54	0.00
6/4/92	dry	dry	dry	dry	0.0000	5941.93	5952.51	0.00
6/7/92	dry	dry	dry	dry	0.0000	5941.78	5952.37	0.00
6/15/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
6/19/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
6/22/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
6/26/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
6/29/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
7/8/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
7/13/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
7/24/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
7/27/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
7/31/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
8/3/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
8/7/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
8/13/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
8/20/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
8/25/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
8/26/92	dry	dry	dry	dry	0.0000	dry	dry	0.00
9/3/92	dry	dry	dry	dry		dry	dry	

3 ft piez.									
	Stream	Farthest		Original				Packed	Stream
Date	Flow	0	25	25	75	105	145	180	Flow
2/25/92	n/a	5886.24	5889.16		n/a		5894.10	5895.61	n/a
3/5/92	n/a	5886.31	5889.18		n/a		5894.26	5895.43	n/a
3/9/92	n/a	5886.33	5889.24		n/a		5894.58	5896.28	n/a
3/10/92	n/a	5886.34	5889.26		n/a		5894.67	5896.52	n/a
3/12/92	n/a	5886.35	5889.29		5891.41		5894.79	5896.78	n/a
3/27/92	n/a	5886.46	5889.44		5891.56		5895.13	5897.13	n/a
3/30/92	n/a	5886.48	5889.46		5891.59		5895.03	5897.09	n/a
3/31/92	n/a	5886.48	5889.47		5891.60		5895.02	5897.09	n/a
4/1/92	n/a	5886.50	5889.45		5891.58		5895.01	5897.07	n/a
4/2/92	n/a	5886.51	5889.44		5891.56		5894.97	5897.06	n/a
4/3/92	n/a	5886.51	5889.43		5891.56		5894.97	5897.05	n/a
4/4/92	n/a	5886.52	5889.43		5891.55		5895.08	5897.21	n/a
4/5/92	n/a	5886.53	5889.42		5891.55		5895.18	5897.05	n/a
4/6/92	n/a	5886.53	5889.41		5891.54		5894.95	5897.04	n/a
4/7/92	n/a	5886.54	5889.40		5891.54		5894.94	5897.17	n/a
4/9/92	n/a	5886.55	5889.39		5891.52		5894.92	5897.04	n/a
4/13/92	n/a	5886.57	5889.36		5891.50		5894.92	5897.10	n/a
4/16/92	n/a	5886.59	5889.37		5891.52		5894.92	5897.03	n/a
4/20/92	n/a	5886.60	5889.32		5891.54		5895.08	5896.99	n/a
4/22/92	0.1487	5886.61	5889.31		5891.47		5895.13	5896.98	n/a
4/24/92	0.1269	5886.60	5889.28		5891.43		5894.85	5896.95	n/a
4/29/92	0.0715	5886.61	5889.24		5891.43		5894.87	5896.92	n/a
5/4/92	0.0712	5886.64	5889.24		5891.42		5894.83	5896.85	0.0000
5/6/92	0.0697	5886.65	5889.22		5891.42		5894.82	5896.77	0.0000
5/8/92	0.0627	5886.65	5889.23		5891.41		5894.88	5896.83	0.0000
5/18/92	0.0523	5886.71	5889.22		5891.42		5894.63	5896.36	0.0000
5/21/92	0.0548	5886.71	5889.30		5891.43		n/a	5896.27	0.0000
5/22/92	0.0554	5886.72	5889.28		5891.42		5894.54	5896.19	0.0000
5/26/92	0.0436	5886.73	5889.24		5891.37		5894.48	5895.88	0.0000
5/27/92	0.0436	5886.78	5889.32		5891.42		5894.35	5895.90	0.0000
5/27/92	0.0436	5886.79	5889.32		5891.42		5894.34	5895.88	0.0000
5/28/92	0.0436	5886.78	5889.29		5891.38		5894.30	5895.84	0.0000
5/28/92	0.0439	5886.78	5889.29		5891.40		5894.28	5895.80	0.0000
5/29/92	0.0415	5886.78	5889.26		5891.39		5894.27	5895.79	0.0000
5/30/92	0.0404	5886.77	5889.29		5891.36		5894.22	5895.77	0.0000
6/1/92	0.0470	5886.81	5889.31		5891.38		5894.25	5895.79	0.0000
6/1/92	0.0529	5886.79	5889.31		5891.38		5894.26	5895.95	0.0000
6/2/92	0.0470	5886.82	5889.32		5891.34		5894.26	5895.89	0.0000
6/2/92	0.0459	dry	5889.29		5891.35		5894.26	5895.88	0.0000
6/3/92	0.0470	dry	5889.30		5891.35		5894.23	5895.86	0.0000
6/4/92	0.0447	dry	5889.30		5891.34		5894.22	5895.83	0.0000
6/4/92	0.0402	dry	5889.30		5891.35		5894.22	5895.83	0.0000
6/7/92	0.0403	dry	5889.11		5891.33		5894.19	5895.79	0.0000
6/15/92	0.0379	dry	5889.34		5891.27		n/a	5895.60	0.0000
6/19/92	0.0326	dry	5889.32		5891.26		n/a	5895.35	0.0000
6/22/92	0.0259	dry	5889.33		5891.24		n/a	5895.02	0.0000
6/26/92	0.0178	dry	5889.43		5891.22		n/a	5894.43	0.0000
6/29/92	0.0111	dry	5889.30		5891.17		n/a	5894.02	0.0000
7/8/92	0.0013	dry	5889.20		5891.08		n/a	dry	0.0000
7/13/92	0.0000	dry	5889.16		5891.03		n/a	dry	0.0000
7/24/92	0.0000	dry	5888.77		5890.47		n/a	dry	0.0000
7/27/92	0.0000	dry	5888.54		5890.24		n/a	dry	0.0000
7/31/92	0.0000	dry	5888.22		5889.99		n/a	dry	0.0000
8/3/92	0.0000	dry	5888.05		5889.77		n/a	dry	0.0000
8/7/92	0.0000	dry	5887.74		dry		n/a	dry	0.0000
8/13/92	0.0000	dry	5887.52		dry		n/a	dry	0.0000
8/20/92	0.0000	dry	5887.09		dry		n/a	dry	0.0000
8/25/92	0.0000	dry	5887.62		dry		n/a	dry	0.0000
8/26/92	0.0000	dry	5887.44		dry		n/a	dry	0.0000
9/3/92		dry	dry		dry		n/a	dry	

3 ft piez.								
					Stream			Stream
Date	330	480	630	780	Flow	930	1080	Flow
2/25/92	dry	dry	dry	dry	n/a	5941.62	5951.79	n/a
3/5/92	dry	5910.06	5922.22	5930.32	n/a	5942.36	5952.58	n/a
3/9/92	5904.57	5911.94	5922.81	5931.07	n/a	5942.52	5952.83	n/a
3/10/92	5904.66	5912.15	5922.91	5931.13	n/a	5942.54	5952.84	n/a
3/12/92	5904.83	5912.42	5923.06	5931.07	n/a	5942.58	5952.89	n/a
3/27/92	5904.82	5912.55	5923.05	dry	n/a	5942.67	5953.08	n/a
3/30/92	5904.53	5912.45	5922.96	dry	n/a	5942.73	5953.25	n/a
3/31/92	5904.46	5912.40	5922.89	dry	n/a	5942.72	5953.25	n/a
4/1/92	5904.35	5912.35	5922.79	dry	n/a	5942.70	5953.23	n/a
4/2/92	5904.30	5912.30	5922.73	dry	n/a	5942.68	5953.21	n/a
4/3/92	5904.29	5912.28	5922.68	dry	n/a	5942.66	5953.21	n/a
4/4/92	5904.51	5912.25	5922.63	dry	n/a	5942.65	5953.20	n/a
4/5/92	5904.44	5912.28	5922.57	dry	n/a	5942.63	5953.20	n/a
4/6/92	5904.24	5912.19	5922.53	dry	n/a	5942.63	5953.19	n/a
4/7/92	5904.21	5912.17	5922.46	dry	n/a	5942.61	5953.16	n/a
4/9/92	5904.32	5912.12	5922.35	dry	n/a	5942.59	5953.16	n/a
4/13/92	5904.37	5912.06	5922.18	dry	n/a	5942.55	5953.08	n/a
4/16/92	5904.24	5911.98	5922.06	dry	n/a	5942.54	5953.05	n/a
4/20/92	5904.08	5911.82	5921.85	dry	n/a	5942.47	5952.98	n/a
4/22/92	5904.01	5911.74	5921.22	dry	n/a	5942.43	5952.98	0.1016
4/24/92	5904.31	5911.63	5921.60	dry	n/a	5942.36	5952.89	0.0772
4/29/92	5903.77	5911.39	5921.36	dry	n/a	5942.28	5952.83	0.0118
5/4/92	5903.31	5910.85	5920.96	dry	0.0165	5942.19	5952.67	0.0038
5/6/92	dry	5910.48	5920.93	dry	0.0243	5942.13	5952.59	0.0000
5/8/92	dry	5910.20	5920.66	dry	0.0029	5942.07	5952.48	0.0000
5/18/92	dry	dry	dry	dry	0.0000	5941.22	5951.67	0.0000
5/21/92	dry	dry	dry	dry	0.0000	n/a	n/a	n/a
5/22/92	dry	dry	dry	dry	0.0000	5940.56	5950.87	0.0000
5/26/92	dry	dry	dry	dry	0.0000	5940.67	5952.21	0.0000
5/27/92	dry	dry	dry	dry	0.0000	5941.14	5952.41	0.0135
5/27/92	dry	dry	dry	dry	0.0000	5941.22	5952.44	0.0078
5/28/92	dry	dry	dry	dry	0.0088	5941.42	5952.50	0.0273
5/28/92	dry	dry	dry	dry	0.0018	5941.46	5952.50	0.0145
5/29/92	dry	dry	dry	dry	0.0000	5941.57	5952.50	0.0000
5/30/92	dry	dry	dry	dry	0.0000	5941.54	5952.39	0.0000
6/1/92	5903.69	dry	dry	dry	0.0000	5941.76	5952.60	0.0000
6/1/92	dry	dry	dry	dry	0.0464	5941.84	5952.62	0.0819
6/2/92	dry	dry	dry	dry	0.0301	5941.89	5952.67	0.0442
6/2/92	dry	dry	dry	dry	0.0047	5941.90	5952.63	0.0106
6/3/92	dry	dry	dry	dry	0.0000	5941.90	5952.57	0.0000
6/4/92	dry	dry	dry	dry	0.0000	5941.90	5952.50	0.0000
6/4/92	dry	dry	dry	dry	0.0000	5941.90	5952.50	0.0000
6/7/92	dry	dry	dry	dry	0.0000	5941.79	5952.18	0.0000
6/15/92	dry	dry	dry	dry	0.0000	dry	5950.93	0.0000
6/19/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
6/22/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
6/26/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
6/29/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
7/8/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
7/13/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
7/24/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
7/27/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
7/31/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
8/3/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
8/7/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
8/13/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
8/20/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
8/25/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
8/26/92	dry	dry	dry	dry	0.0000	dry	dry	0.0000
9/3/92	dry	dry	dry	dry		dry	dry	

APPENDIX B

Air Permeameter Data

Streambed traverse at various locations

		0"	3"	6"	9"	12"	15"
29 ft U/S	Time(sec)		0.99	1.4	1.01	1.06	0.99
	K(m/s)		1.1E-4	7.7E-5	1.1E-4	1.1E-4	1.1E-4
30 ft U/S	Time(sec)		2.1	1.06	1.18	1.17	1.22
	K(m/s)		4.9E-5	1.1E-4	9.4E-5	9.4E-5	9.0E-5
340 ft U/S	Time(sec)	1.37	1.14	1.41	1.18	1.09	1.39
	K(m/s)	7.9E-5	9.7E-5	7.7E-5	9.4E-5	1.0E-4	7.8E-5
341 ft U/S	Time(sec)		1.11	1.23	1.2	1.67	1.43
	K(m/s)		1.0E-4	9.0E-5	9.2E-5	6.4E-5	7.8E-5

		18"	21"	24"	27"	30"	33"
29 ft U/S	Time(sec)	1.12	1.33	0.97	1.01	1.06	3.41
	K(m/s)	9.9E-5	8.2E-5	1.2E-4	1.1E-4	1.1E-4	2.9E-5
30 ft U/S	Time(sec)	1,02	1	0.97	1.04	2	0.97
	K(m/s)	1.1E-4	1.1E-4	1.2E-4	1.0E-4	5.2E-5	1.2E-4
340 ft U/S	Time(sec)	1.59	1.6				
	K(m/s)	6.7E-5	6.7E-5				
341 ft U/S	Time(sec)						
	K(m/s)						

		36"	39"	Average	STDEV
29 ft U/S	Time(sec)				
	K(m/s)			9.7E-5	2.6E-5
30 ft U/S	Time(sec)	1.64	1.53		
	K(m/s)	6.5E-5	7.0E-5	9.1E-5	2.4E-5
340 ft U/S	Time(sec)				
	K(m/s)			8.3E-5	1.4E-5
341 ft U/S	Time(sec)				
	K(m/s)			8.4E-5	1.5E-5

Vertical section at 180 ft U/S piezometer set

times (sec)

	1 Foot		2 Foot		3 Foot	
depth	U/S	D/S	U/S	D/S	U/S	D/S
3"			1.23	3.74		1.07
6"					2.18	0.94
9"				1.05		
12"	4.06		1.07	1.06	1.49	0.95
15"			2.68	1.13		
18"			2.87	14.3		
21"			12.13	1.77	3.34	1.85
24"			1.06	1.43	3.87	1.81
27"					1.11	1.25
30"					1.28	1.62
33"					0.96	
36"					1.07	1.25
Average	2.43		3.13	3.06	1.68	1.116
SDEV			4.16	4.08	1.16	-0.53

K (m/s)

	1 Foot		2 Foot		3 Foot			
depth	U/S	D/S	U/S	D/S	U/S	D/S	Average	SDEV
3"			8.2E-5	2.6E-5		1.0E-4	7.1E-5	4.0E-5
6"					4.7E-5	1.2E-4	8.4E-5	5.2E-5
9"				1.1E-4			1.1E-4	
12"	1.9E-5		1.0E-4	1.1E-4	7.3E-5	1.2E-4	8.4E-5	4.0E-5
15"			3.8E-5	9.8E-5			6.8E-5	4.3E-5
18"			2.6E-5	5.8E-6			1.6E-5	1.5E-5
21"			7.0E-6	6.0E-5	2.9E-5	5.7E-5	3.8E-5	2.5E-5
24"			1.1E-4	7.6E-5	2.6E-5	7.1E-5	7.1E-5	3.3E-5
27"					1.0E-4	8.8E-5	9.4E-5	9.0E-6
30"					8.6E-5	6.5E-5	7.6E-5	1.5E-5
33"					1.2E-4		1.2E-4	
36"					1.0E-4	8.8E-5	9.4E-5	1.2E-5
Average	1.9E-5		6.0E-5	6.8E-5	7.3E-5	8.9E-5	all meas.	
SDEV			4.2E-5	4.0E-5	3.6E-5	2.4E-5	7.7E-5	3.6E-5

Vertical section at pit at 380 ft U/S

	times (sec)		K (m/s)					
depth	NW wall	SW wall	NW wall	SW wall	Average	STDEV		
3"	0.98		1.1E-4		1.1E-4			
6"	1.71	10.27	6.2E-5	8.4E-6	3.5E-5	3.8E-5	upper	
9"	1.22	2.12	9.1E-5	3.2E-5	6.2E-5	4.2E-5	layer:	
12"	1.18	3.25	9.4E-5	3.0E-5	6.2E-5	4.5E-5	6.7E-5	4.2E-5
15"	0.94	0.97	1.2E-4	1.2E-4	1.2E-4	2.9E-6		
18"		0.90		1.1E-4	1.1E-4		lower	
21"	1.04	0.94	1.1E-4	1.2E-4	1.2E-4	9.4E-6	layer:	
24"		0.91		1.3E-4	1.3E-4		1.2E-4	6.2E-6
Average	1.18	2.92	9.8E-5	7.8E-5				
STDEV	0.26	3.41	2.1E-5	5.2E-5				

APPENDIX C

Precipitation

date	inches
4/9/92	
4/10/92	
4/11/92	0.1
4/12/92	
4/13/92	
4/14/92	0.16
4/15/92	0.12
4/16/92	0.07
4/17/92	
4/18/92	
4/19/92	
4/20/92	
4/21/92	
4/22/92	0.13
4/23/92	
4/24/92	
4/25/92	
4/26/92	
4/27/92	
4/28/92	
4/29/92	
4/30/92	
5/1/92	
5/2/92	
5/3/92	
5/4/92	
5/5/92	
5/6/92	
5/7/92	
5/8/92	
5/9/92	0.13
5/10/92	
5/11/92	
5/12/92	
5/13/92	
5/14/92	
5/15/92	
5/16/92	
5/17/92	
5/18/92	
5/19/92	0.18
5/20/92	

5/21/92	0.39
5/22/92	0.18
5/23/92	
5/24/92	0.06
5/25/92	0.58
5/26/92	0.15
5/27/92	0.18
5/28/92	0.08
5/29/92	
5/30/92	0.02
5/31/92	0.36
6/1/92	0.39
6/2/92	
6/3/92	
6/4/92	
6/5/92	0.14
6/6/92	
6/7/92	0.1
6/8/92	0.05
6/9/92	
6/10/92	
6/11/92	
6/12/92	
6/13/92	0.02
6/14/92	0.01
6/15/92	
6/16/92	
6/17/92	
6/18/92	
6/19/92	0.05
6/20/92	
6/21/92	
6/22/92	
6/23/92	0.02
6/24/92	
6/25/92	0.1
6/26/92	0.1
6/27/92	
6/28/92	0.03
6/29/92	
6/30/92	
7/1/92	0.06
7/2/92	0.23
7/3/92	

CWRRI	Sept. 1992
CSM Survey Field	2
Jefferson County	150
Stream-Groundwater Interaction	GEOMETRICS hammer

Hammer SHOT: 1 LOCATION: 1.00 ELEVATION: 5898.13 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
11.0000	25.500	5809.3501
12.0000	25.900	5809.7002
14.0000	28.400	5809.8701
15.0000	29.600	5900.0400
16.0000	29.200	5900.2202
17.0000	29.900	5900.3901
18.0000	30.200	5900.5601
19.0000	30.900	5900.7402
20.0000	31.000	5900.9102
22.0000	31.400	5901.2598

SHOT: 2 LOCATION: 4.00 ELEVATION: 5898.19 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
11.0000	19.500	5809.3501
12.0000	22.000	5809.5200
13.0000	24.800	5809.7002
14.0000	27.200	5809.8701
15.0000	29.000	5900.0400
16.0000	28.500	5900.2202
17.0000	28.700	5900.3901
18.0000	29.000	5900.5601
19.0000	29.800	5900.7402
20.0000	30.000	5900.9102
22.0000	30.600	5901.2598

SHOT: 3 LOCATION: 8.00 ELEVATION: 5898.77 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
11.0000	19.500	5809.3501
12.0000	22.000	5809.5200
13.0000	25.000	5809.7002
14.0000	27.000	5809.8701
15.0000	28.000	5900.0400
16.0000	28.000	5900.2202
17.0000	29.000	5900.3901
18.0000	29.000	5900.5601
19.0000	29.000	5900.7402
20.0000	29.200	5900.9102
22.0000	30.000	5901.8398

SHOT: 4 LOCATION: 25.00 ELEVATION: 5901.84 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
11.0000	27.700	5809.3501
12.0000	27.200	5809.5200
13.0000	28.000	5809.7002
14.0000	28.000	5809.8701
15.0000	28.000	5900.0400
16.0000	27.200	5900.2202
17.0000	26.000	5900.3901
18.0000	24.200	5900.5601
19.0000	22.000	5900.7402
20.0000	19.700	5900.9102
22.0000	15.000	5901.2598

SHOT: 5 LOCATION: 28.00 ELEVATION: 5902.41 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
11.0000	31.500	5809.3501
12.0000	31.000	5809.5200
13.0000	32.000	5809.7002
14.0000	31.800	5809.8701
15.0000	32.600	5900.0400
16.0000	31.300	5900.2202
17.0000	32.700	5900.3901
18.0000	32.000	5900.5601
19.0000	30.000	5900.7402
20.0000	27.200	5900.9102
22.0000	25.000	5901.2598

SHOT: 6 LOCATION: 31.00 ELEVATION: 5902.41 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION11
.0000	33.100	5809.3501
12.0000	33.000	5809.5200
13.0000	33.300	5809.7002
14.0000	33.400	5809.8701
15.0000	33.700	5900.0400
16.0000	32.300	5900.2202
17.0000	32.300	5900.3901
18.0000	32.000	5900.5601
19.0000	31.800	5900.7402
20.0000	31.000	5900.9102
22.0000	28.500	5901.2598

CWRRI	Sept, 1992
CSM Survey Field	C
Jefferson County	150
Stream/GW Interaction	GEOMETRICS hammer

SHOT: 1 LOCATION: 84.00 ELEVATION: 5906.50 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
93.0000	24.000	5908.0601
95.0000	24.800	5908.2500
96.0000	25.100	5908.4502
97.0000	27.000	5908.6401
98.0000	27.900	5908.8398
99.0000	28.600	5909.0298
100.0000	29.000	5909.2300
101.0000	29.500	5909.4199
102.0000	30.000	5909.6099
103.0000	30.800	5909.8101
104.0000	31.500	5900.2002

SHOT: 2 LOCATION: 88.00 ELEVATION: 5907.28 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
93.0000	17.500	5908.0601
95.0000	21.200	5908.2500
96.0000	22.400	5908.4502
97.0000	23.000	5908.6401
98.0000	24.600	5908.8398
99.0000	25.500	5909.0298
100.0000	25.500	5909.2300
101.0000	26.000	5909.4199
102.0000	27.000	5909.6099
103.0000	27.500	5909.8101
104.0000	28.300	5900.2002

SHOT: 3 LOCATION: 92.00 ELEVATION: 5907.86 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
93.0000	10.100	5908.0601
95.0000	15.500	5908.2500
96.0000	18.000	5908.4502
97.0000	20.000	5908.6401
98.0000	21.800	5908.8398
99.0000	23.000	5909.0298
100.0000	24.000	5909.2300
101.0000	24.600	5909.4199
102.0000	25.000	5909.6099
103.0000	26.000	5909.8101
104.0000	27.000	5900.2002

SHOT: 4 LOCATION: 105.00 ELEVATION: 5910.39 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
93.0000	26.700	5908.0601
95.0000	25.000	5908.2500
96.0000	25.000	5908.4502
97.0000	25.000	5908.6401
98.0000	23.200	5908.8398
99.0000	23.000	5909.0298
100.0000	19.200	5909.2300
101.0000	16.700	5909.4199
102.0000	14.200	5909.6099
103.0000	10.900	5909.8101
104.0000	9.6000	5910.2002

SHOT: 5 LOCATION: 108.00 ELEVATION: 5910.00 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
93.0000	30.500	5908.0601
95.0000	28.600	5908.2500
96.0000	28.700	5908.4502
97.0000	28.500	5908.6401
98.0000	27.000	5908.8398
99.0000	26.000	5909.0298
100.0000	26.000	5909.2300
101.0000	26.000	5909.4199
102.0000	25.000	5909.6099
103.0000	22.000	5909.8101
104.0000	18.200	5900.2002

SHOT: 6 LOCATION: 112.00 ELEVATION: 5910.00 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
93.0000	32.000	5908.0601
95.0000	30.500	5908.2500
96.0000	30.500	5908.4502
97.0000	30.400	5908.6401
98.0000	30.000	5908.8398
99.0000	28.800	5909.0298
100.0000	29.000	5909.2300
101.0000	27.500	5909.4199
102.0000	27.000	5909.6099
103.0000	26.800	5909.8101
104.0000	26.500	5900.2002

CWRRI	Sept, 1992
CSM Survey Field	D
Jefferson County, Colorado	150
Stream/GW Interaction	GEOMETRICS hammer

hammer SHOT: 1 LOCATION: 143.00 ELEVATION: 5921.90 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
151.0000	23.000	5904.0000
153.0000	24.000	5904.5298
154.0000	25.500	5904.7900
155.0000	26.500	5905.0498
156.0000	27.000	5905.3101
157.0000	27.400	5905.5801
158.0000	28.000	5905.8398
159.0000	28.300	5906.1001
160.0000	28.700	5906.3599
161.0000	28.900	5906.6299
162.0000	30.000	5906.8901

SHOT: 2 LOCATION: 147.00 ELEVATION: 5922.95 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
151.0000	13.200	5904.0000
153.0000	18.000	5904.5298
154.0000	19.800	5904.7900
155.0000	21.000	5905.0498
156.0000	22.200	5905.3101
157.0000	23.800	5905.5801
158.0000	24.000	5905.8398
159.0000	24.000	5906.1001
160.0000	24.300	5906.3599
161.0000	26.000	5906.6299
162.0000	28.000	5906.8901

SHOT: 3 LOCATION: 150.00 ELEVATION: 5923.74 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
155.0000	21.000	5925.0508
156.0000	18.200	5925.3101
157.0000	20.800	5925.5801
158.0000	21.200	5925.8398
159.0000	22.500	5926.1001
160.0000	23.500	5926.3599
161.0000	24.000	5926.6299
162.0000	25.000	5926.8901

SHOT: 4 LOCATION: 163.00 ELEVATION: 5927.15 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
151.0000	24.800	5904.0000
153.0000	24.700	5904.5298
154.0000	24.500	5904.7900
155.0000	24.200	5905.0498
156.0000	22.000	5905.3101
157.0000	21.400	5905.5801
158.0000	18.000	5905.8398
159.0000	16.000	5906.1001
160.0000	15.000	5906.3599
161.0000	12.300	5906.6299
162.0000	8.0000	5926.8901

SHOT: 5 LOCATION: 166.00 ELEVATION: 5927.94 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
151.0000	36.000	5904.0000
153.0000	33.000	5904.5298
154.0000	31.900	5904.7900
155.0000	29.000	5905.0498
156.0000	27.000	5905.3101
157.0000	25.000	5905.5801
158.0000	23.100	5905.8398
159.0000	22.000	5906.1001
160.0000	20.800	5906.3599
161.0000	18.800	5906.6299
162.0000	16.000	5906.8901

SHOT: 6 LOCATION: 170.00 ELEVATION: 5928.99 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
153.0000	28.500	5904.5298
154.0000	27.000	5904.7900
155.0000	26.500	5904.0498
156.0000	26.200	5905.3101
157.0000	26.000	5905.5801
158.0000	25.600	5905.8398
159.0000	25.100	5905.1001
160.0000	24.900	5906.3599
161.0000	25.000	5906.6299
162.0000	23.000	5906.8901

CWRRI Sept, 1992
CSM Survey Field E
Jefferson County. Colorado 150
Stream/GW Interaction GEOMETRICS hammer

Hammer SHOT: 1 LOCATION: 205.00 ELEVATION: 5950.00 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
213.0000	31.000	5902.6665
215.0000	31.800	5903.3335
216.0000	33.000	5903.6665
217.0000	33.300	5904.0000
218.0000	33.300	5904.3335
219.0000	33.000	5904.6665
220.0000	34.000	5905.0000
221.0000	34.200	5905.3335
222.0000	34.500	5905.6665
223.0000	34.800	5906.0000
224.0000	35.000	5906.3335

SHOT: 2 LOCATION: 209.00 ELEVATION: 5951.33 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
213.0000	17.000	5902.6665
215.0000	23.000	5903.3335
216.0000	28.000	5903.6665
217.0000	31.000	5904.0000
218.0000	31.500	5904.3335
219.0000	32.000	5904.6665
220.0000	32.200	5905.0000
221.0000	33.000	5905.3335
222.0000	33.000	5905.6665
223.0000	34.000	5906.0000
224.0000	35.000	5906.3335

SHOT: 4 LOCATION: 225.00 ELEVATION: 5956.67 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
213.0000	31.000	5902.6665
215.0000	30.800	5903.3335
216.0000	30.800	5903.6665
217.0000	29.500	5904.0000
218.0000	26.500	5904.3335
219.0000	22.800	5904.6665
220.0000	19.000	5905.0000
221.0000	15.500	5905.3335
222.0000	12.000	5905.6665
223.0000	8.8000	5956.0000
224.0000	4.9000	5956.3335

SHOT: 5 LOCATION: 228.00 ELEVATION: 5957.67 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
213.0000	32.800	5902.6665
215.0000	32.300	5903.3335
216.0000	31.500	5903.6665
217.0000	30.00	5904.0000
218.0000	30.600	5904.3335
219.0000	29.500	5904.6665
220.0000	29.000	5905.0000
221.0000	25.500	5905.3335
222.0000	22.000	5905.6665
223.0000	19.000	5906.0000
224.0000	15.000	5906.3335

SHOT: 6 LOCATION: 232.00 ELEVATION: 5959.00 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
213.0000	33.700	5902.6665
216.0000	32.000	5903.6665
217.0000	31.500	5904.0000
218.0000	30.700	5904.3335
219.0000	29.500	5904.6665
220.0000	28.000	5905.0000
221.0000	28.600	5905.3335
222.0000	27.100	5905.6665
223.0000	26.500	5906.0000
224.0000	25.000	5906.3335

CWRRI	Sept, 1992
CSM Survey Field	F
Jefferson County. Colorado	150
Stream/GW Interaction	GEOMETRICS hammer

Hammer SHOT: 1 LOCATION: 255.00 ELEVATION: 5956.00 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
263.0000	18.000	5904.0000
265.0000	18.500	5904.7998
266.0000	18.800	5905.2002
267.0000	19.200	5905.6001
268.0000	19.800	5905.9902
269.0000	20.000	5906.3901
270.0000	20.000	5906.7900
271.0000	21.700	5907.1899
272.0000	22.200	5907.5898
273.0000	23.800	5907.9902
274.0000	23.800	5908.3901

SHOT: 2 LOCATION: 259.00 ELEVATION: 5955.00 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
263.0000	16.400	5904.0000
265.0000	18.000	5904.7998
266.0000	18.000	5905.2002
267.0000	18.300	5905.6001
268.0000	19.000	5905.9902
269.0000	19.000	5906.3901
270.0000	19.000	5906.7900
271.0000	20.900	5907.1899
272.0000	21.000	5907.5898
273.0000	21.500	5907.9902
274.0000	21.500	5908.3901

SHOT: 3 LOCATION: 262.00 ELEVATION: 5954.25 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
263.0000	18.200	5904.0000
265.0000	28.000	5904.7998
266.0000	32.000	5905.2002
267.0000	34.000	5905.6001
268.0000	37.500	5905.9902
269.0000	39.500	5906.3901
270.0000	42.000	5906.7900
271.0000	44.900	5907.1899
272.0000	46.000	5907.5898
273.0000	49.000	5907.9902
274.0000	51.000	5908.3901

SHOT: 4 LOCATION: 275.00 ELEVATION: 5958.79 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
263.0000	24.000	5904.0000
265.0000	23.000	5904.7998
266.0000	21.000	5905.2002
267.0000	21.000	5905.6001
268.0000	21.000	5905.9902
269.0000	20.200	5906.3901
270.0000	19.700	5906.7900
271.0000	19.700	5907.1899
272.0000	17.000	5907.5898
273.0000	15.000	5907.9902
274.0000	11.700	5908.3901

SHOT: 5 LOCATION: 278.00 ELEVATION: 5959.98 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
263.0000	25.000	5904.0000
265.0000	24.000	5904.7998
266.0000	23.800	5905.2002
267.0000	23.000	5905.6001
268.0000	23.000	5905.9902
269.0000	22.100	5906.3901
270.0000	21.000	5906.7900
271.0000	21.000	5907.1899
272.0000	20.500	5907.5898
273.0000	19.700	5907.9902
274.0000	18.000	5908.3901

SHOT: 6 LOCATION: 282.00 ELEVATION: 5961.58 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
263.0000	25.700	5904.0000
265.0000	25.500	5904.7998
266.0000	24.500	5905.2002
267.0000	24.000	5905.6001
268.0000	23.800	5905.9902
269.0000	22.500	5906.3901
270.0000	22.500	5906.7900
271.0000	22.000	5907.1899
272.0000	21.000	5907.5898
273.0000	21.000	5907.9902
274.0000	20.000	5908.3901

CWRRI	Sept, 1992
CSM Survey Field	G
Jefferson County, Colorado	150
Stream/GW Interaction	GEOMETRICS hammer

Hammer SHOT: 1 LOCATION: 143.00 ELEVATION: 5924.56 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
151.0000	26.000	5906.8101
152.0000	26.800	5907.0898
153.0000	26.000	5907.3799
154.0000	26.000	5907.6602
155.0000	28.000	5907.9399
156.0000	28.700	5908.2202
157.0000	29.000	5908.5000
158.0000	30.000	5908.7798
159.0000	31.000	5909.0698
160.0000	31.300	5909.3501
162.0000	33.100	5909.9102

SHOT: 2 LOCATION: 147.00 ELEVATION: 5925.68 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
151.0000	22.000	5906.8101
152.0000	22.800	5907.0898
153.0000	23.000	5907.3799
154.0000	23.300	5907.6602
155.0000	24.000	5907.9399
156.0000	25.000	5908.2202
157.0000	25.200	5908.5000
158.0000	26.100	5908.7798
159.0000	27.300	5909.0698
160.0000	27.800	5909.3501
162.0000	29.500	5909.9102

SHOT: 3 LOCATION: 150.00 ELEVATION: 5926.53 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
152.0000	12.800	5907.0898
153.0000	14.000	5907.3799
154.0000	15.700	5907.6602
155.0000	18.000	5907.9399
156.0000	19.000	5908.2202
157.0000	20.000	5908.5000
158.0000	21.000	5908.7798
159.0000	23.000	5909.0698
160.0000	23.900	5909.3501
162.0000	26.500	5909.9102

SHOT: 4 LOCATION: 163.00 ELEVATION: 5930.19 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
151.0000	27.000	5906.8101
152.0000	26.000	5907.0898
153.0000	24.800	5907.3799
154.0000	23.400	5907.6602
155.0000	22.500	5907.9399
156.0000	22.000	5908.2202
157.0000	21.000	5908.5000
158.0000	19.000	5908.7798
159.0000	18.000	5909.0698
160.0000	14.000	5909.3501
162.0000	7.3000	5929.9102

SHOT: 5 LOCATION: 166.00 ELEVATION: 5931.04 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
151.0000	27.200	5906.8101
152.0000	26.500	5907.0898
153.0000	25.200	5907.3799
154.0000	24.000	5907.6602
155.0000	24.300	5907.9399
156.0000	24.000	5908.2202
157.0000	23.000	5908.5000
158.0000	22.500	5908.7798
159.0000	22.000	5909.0698
160.0000	20.800	5909.3501
162.0000	18.000	5909.9102

SHOT: 6 LOCATION: 170.00 ELEVATION: 5932.17 DEPTH: 0.00

POSITION	TRAVEL TIME	ELEVATION
151.0000	25.200	5906.8101
152.0000	24.800	5907.0898
153.0000	23.500	5907.3799
154.0000	23.000	5907.6602
155.0000	23.000	5907.9399
156.0000	23.000	5908.2202
157.0000	22.000	5908.5000
158.0000	21.800	5908.7798
159.0000	21.500	5909.0698
160.0000	20.800	5909.3501
162.0000	20.000	5909.9102