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TECHNICAL MEMORANDUM

TO: **Andrew Burns - Southern Nevada Water Authority** **HCI-1827**
Jim Watrus - Southern Nevada Water Authority

FROM: **Houmao Liu**

SUBJECT: **Comparison of Calculations by *FEMFLOW3D* and *MODFLOW* for a Contrived Ground-Water Flow Problem Involving a Two-Compartment System Separated by a Low Permeability Fault**

DATE: **June 28, 2006**

INTRODUCTION

Hydrologic Consultants, Inc. (HCI) has previously submitted three technical memoranda to the Southern Nevada Water Authority (SNWA). The first one (HCI, 2006a) summarized our review of the document entitled "*FEMFLOW3D* - A Finite-Element Program for the Simulation of Three-Dimensional Groundwater Systems, Version 2". The second technical memorandum (HCI, 2006b) summarized our review of the source code of *FEMFLOW3D* (written in *FORTRAN)* and comparisons between model-calculated and analytical solutions to some very simple ground-water flow problems (e.g., the Theis solution). The third one (HCI, 2006c) summarized our comparative findings from simulations of a contrived ground-water flow problem involving a laterally continuous (or so-called single compartment) system using both *FEMFLOW3D* and *MODFLOW*.

This fourth technical memorandum summarizes the findings from our numerical simulations of another contrived ground-water flow problem involving two "compartments" separated by a low permeability fault using both *FEMFLOW3D* and *MODFLOW*. This problem was chosen because *FEMFLOW3D* uses fault planes to divide a model domain into a series of compartments whereas *MODFLOW* simulates a similar condition using what is called a *Horizontal Flow Barrier (HFB).*

Initially, it was also planned to compare simulations of the two-compartment system separated by a high permeability fault using both Version 1 and Version 2 of *FEMFLOW3D* (HCI, 2006d). However, Timothy J. Durbin, author of *FEMFLOW3D*, is of the opinion that the approach used in Version 1 of *FEMFLOW3D* for simulating high permeability faults is so significantly different from that used in Version 2 of *FEMFLOW3D* that there is no equivalent way to compare the simulated results from the two versions of the codes. As a consequence, SNWA asked HCI to first complete the numerical simulations and prepare a technical memorandum on the low permeability fault and then design a method for validating the permeable fault feature of *FEMFLOW3D.*

DESCRIPTION OF CONTRIVED GROUND-WATER FLOW PROBLEM INVOLVING TWO COMPARTMENTS SEPARATED BY A LOW PERMEABILITY FAULT

Background

The ground-water flow problem involving two-compartments separated by a low permeability fault is similar in most respects to the problem with a laterally continuous -- or single compartment -- flow system described in (HCI, 2006c). The only difference is that the two-compartment problem incorporates a low permeability fault at 50,000 ft East that divides the model domain into two compartments, the so-called Western and Eastern Compartments (Figure 1).

As shown in Figures 1 and 2, the two-compartment problem incorporates the following features and components:

1) A defined topographic surface including two streams separated by a topographic divide, forming two basins.

2) Orographically-controlled recharge to enable, together with the streams, a hydrologic divide to develop in at least the top layer of the model.

3) Two hydrogeologic layers, which are further sub-divided into more model layers for numerical purposes, with a water table in the upper hydrogeologic layer and with the lower hydrogeologic layer significantly more permeable than the upper layer.

4) A set of defined hydraulic properties for the two hydrogeologic layers and stream characteristics.

5) Boundary conditions such that the lower hydrogeologic unit could potentially transmit water between the two basins.

6) The ability to run both models (i.e., *FEMFLOW3D* and *MODFLOW* models) to steady-state conditions.

7) The ability to simulate a major, transient, hydraulic stress (in this case, pumping).

8) The two compartments with same hydrogeologic properties as described above.

Description of Conceptual Hydrogeologic Model

Figure 1 is a schematic diagram of the contrived two-compartment problem. The horizontal dimensions of the model domain are 90,000 by 90,000 ft, and the thickness ranges from 3,000 to 4,000 ft. There are two horizontal hydrogeologic units in the model domain, and the hydraulic conductivity of the lower unit is 10 times higher than that of the upper unit. The domain includes two valleys with mountains on the eastern, western, and northern side of each valley. The two valleys are separated by a low permeability fault located at 50,000 ft East. Streams flow in each valley from north to south into a river at the southern edge of the domain that flows from east to west. The western valley contains an area of potential evapotranspiration (ET) near its southern end.

Description of Numerical Models

The domain of this second contrived problem was incorporated into numerical ground-water flow models using *FEMFLOW3D* and *MODFLOW*. In each model, the eastern, western, and northern boundaries are no-flow boundaries (Figure 2). The southern boundary is a constant (or specified head) boundary in all layers, with the specified heads ranging from elevation 3,300 ft NGVD on the east side of the model to 2,980 ft on the west side. This represents a river flowing from east to west and allows inter-basin ground-water flow in the lower hydrogeologic unit. There is no vertical gradient assigned to the specified heads (i.e., the values of the specified heads do not vary in the vertical direction).

The low permeability fault was simulated in *FEMFLOW3D* as a fault plane with a transmissivity (hydraulic conductivity times thickness) value of 0.01 ft^2/day and a transverse "leakance" (hydraulic conductivity divided by thickness) of 1 x 10^{-6} 1/day. In *MODFLOW* model, the low permeability fault was simulated using the *HFB* feature with a thickness of 0.1 ft and a hydraulic conductivity (assumed to be isotropic) of 1.0 x 10^{-7} ft/day. It should be noted that the "exact" transverse leakance defined by:

$$leakance = \frac{K_{HFB}}{w_{HFB}}$$

using the thickness (or width) and hydraulic conductivity value put into *MODFLOW* is 1.0 x 10^{-6} 1/day, which is the same as the value of 1 x 10^{-6} 1/day used in *FEMFLOW3D*.

The hydraulic properties of the two hydrogeologic units are summarized in Table 1. The bottom unit has a uniform thickness of 1,500 ft; the top unit has a thickness ranging from 1,500 to 2,000 ft, depending on the elevation of the ground surface.

Recharge is applied to nodes (using *FEMFLOW3D)* or cells (using *MODFLOW*) along the mountain ranges, comprising a line source (Figure 2). The recharge rate for the *MODFLOW* model is 5.81 in/year. The equivalent flux is applied to each of the recharge nodes in the *FEMFLOW3D* model.

The two streams are represented in the models by using the stream routines of the respective codes. Each stream is assigned a width of 10 ft, a streambed thickness of 1 ft, and a vertical hydraulic conductivity of the streambed of 0.01 ft/day. The elevation of the streambed of the eastern stream decreases from 3,600 ft in the north to 3,200 ft at the river. The elevation of the streambed in the western stream similarly ranges from 3,400 to 3,000 ft. Since the last node (or cell) of each stream is a constant head node (cell), these nodes (cells) are not simulated as part of the stream.

ET is simulated in the southern part of the western valley. An "extinction depth" of 20 ft and a maximum ET rate of 0.8 ft/yr were assigned to the ET area.

A pumping "center" with a large extraction rate was incorporated to simulate a relatively large wellfield in the basin. This pumping center is represented as a single "well" at the center of the model domain (Point B, Figure 2). The model was simulated during the first 20 years of the transient simulations as pumping at a rate of 12.5 cfs (5,600 gpm) and then recovering for the next 60 years. The models attempted to simulate ground-water extraction from both hydrogeologic layers of each model. *FEMFLOW3D* uses a "linking" feature to simulate a well penetrating multiple layers. With *MODFLOW*, the vertical conductivity values for the cells containing the well were set at very high values. During the simulation of recovery, the well linking and high hydraulic conductivity values were turned off in the respective models.

General Set-Up of Models

Figure 3 shows the meshes for the *FEMFLOW3D* and *MODFLOW* models. The set-up of the *FEMFLOW3D* model was done by Timothy J. Durbin, Inc. (TJDI). HCI used *VISUAL MODFLOW PRO* Version 3.1 from Waterloo Hydrogeologic for setting up the *MODFLOW* model. The *FEMFLOW3D* mesh has 3,420 nodes and 5,184 elements; the *MODFLOW* mesh has 3,040 cells. Both models contain eight model layers. The meshes were constructed so that all interior nodes are located in exactly the same location in plan view for both models. The nodes in the *FEMFLOW3D* finite-element model are located at the corners of elements. Nodes in the *MODFLOW* finite-difference model are located in the center of the cells, both horizontally and vertically.

Because of the difference in the fundamental location of the nodes in the two numerical methods (i.e., finite-element vs. finite-difference), the nodes in the two meshes are not in the same locations in the vertical dimension. There are eight nodes in each node column in the finite difference mesh, but nine in the finite element mesh. In this problem, six model layers are used to represent the upper hydrostratigraphic unit, and two model layers are used to represent the lower hydrostratigraphic unit.

Constant heads were assigned to the row of nodes at 5,000 ft North, as shown in Figure 3. The assigned heads of all constant heads used in the models were summarized in the previous technical memorandum (HCI, 2006c) and are not repeated here.

Recharge was applied at a rate of 5.81 in/yr (or 0.001326 ft/day) over the area associated with 62 *MODFLOW* cells (each cell is 5,000 x 5,000 ft in size) for a total of 2.05 x 10^6 ft^3/day (or 23.73 cfs). The same amount of recharge was applied to the 124 nodes in the first and second nodal layers of the *FEMFLOW3D* model mesh.

Streams were defined node-by-node with stream lengths of 5,000 ft in both the *FEMFLOW3D* and *MODFLOW* meshes. The locations and elevations of the stream nodes are summarized in Table 2.

The area of ET was represented by 20 nodes in the *FEMFLOW3D* meshes and 20 cells in the *MODFLOW* mesh, as shown in Figure 3.

RUNNING OF MODELS

Both steady-state and transient model simulations were conducted with *FEMFLOW3D* and *MODFLOW*. Although TJDI prepared the model input files for the *FEMFLOW3D* model and conducted the simulations, HCI interacted closely with TJDI in selecting the hydraulic parameters, setting up the boundary conditions, and evaluating the model results. For the *MODLFOW* simulations, HCI used the *MODFLOW96* numeric engine in *Visual MODFLOW* Version 3.1 because this version of the code provided much faster convergence than *MODFLOW2000* during the 60 years of simulated recovery. It was not an objective of this code validation to evaluate the different versions of *MODFLOW*, so HCI simply selected a *MODFLOW* numerical engine that is applicable to the test problem.

MODEL RESULTS

Presentation of Results

Results from these runs are compared in the form of tables summarizing the steady-state water budgets and a series of contour maps and hydrographs showing water levels calculated by the two models. The three levels in vertical extent of the models that were selected to compare the water levels were:

1) the water table,

2) the lower portion of the upper hydrostratigraphic unit at an elevation of 1,666 ft; and

3) the lower portion of the lower hydrostratigraphic unit at an elevation of 375 ft.

As previously noted, the nodes of the *FEMFLOW3D* and *MODFLOW* meshes coincide in plan view, but they do not coincide in the vertical dimension. Therefore, linear interpolation was used to report heads and drawdowns for the same vertical location.

For *FEMFLOW3D* the following interpolations were made:

1) Heads at the first nodal layer were used for the water table.

2) Heads at elevations of 1,666 and 375 ft were computed by linear interpolation of heads at nodes immediately above and below 1,666 and 375 ft, respectively.

For *MODFLOW*, the following procedures were used to report heads:

1) The water table was reported as the head in the uppermost saturated cell.

2) Heads at elevations of 1,666 and 375 ft were reported as the heads in the cell corresponding to that elevation.

After the heads were computed for each model simulation, the nodal values were imported together with their Northing and Easting coordinates into Golden Software's *SURFER* contouring package. The kriging routine of *SURFER* (using the default options) was used to produce the contour plots described below.

Comparison of Model Results

Before comparing the model results derived from each code, it is worth noting the following differences between *FEMFLOW3D* and *MODFLOW* that can cause slight discrepancies in the results.

1) Calculation of water table

   FEMFLOW3D uses grid collapsing to calculate the water table. *MODFLOW* uses the calculated head in the uppermost saturated cell as the water table. For a water table that fluctuates between different vertical layers, *MODFLOW* uses somewhat arbitrary parameters to control the wetting and drying of model cells.

2) Representation of the pumping well

   FEMFLOW3D uses a well "linking" feature to simulate direct flow between specified well nodes with very little resistance. This was used in the contrived problem to represent a well penetrating several layers. *MODFLOW* does not have this feature; it uses a high vertical hydraulic conductivity value in the column of the cells to simulate a multi-layer pumping well.

2) Representation of the low permeability fault

   As previously described, *FEMFLOW3D* uses its fault routine to simulate a plane with a low longitudinal transmissivity and low transverse leakance. *MODFLOW* simulates the low permeability fault by assigning a low hydraulic conductivity and thickness to the *HFB* routine.

Results of Steady-State Simulations

Figures 4, 5, and 6 are contour plots showing the calculated hydraulic heads at the water table, at the 1,666 ft level, and at the 375 ft level, respectively, by both *FEMFLOW3D* and *MODFLOW* for the contrived two-compartment problem under steady-state conditions. Figures 4, 5, and 6 clearly show that the two hydrologic basins are separated by the impermeable fault in both models. The head differences across the fault are about 50 ft. In all of these figures, the calculated hydraulic heads from both models are essentially identical.

The water budgets under steady-state conditions calculated by the two models for the contrived two-compartment problem are summarized in Table 3. Again, the values from the two models are essentially identical except for the flux from the Eastern to the Western Compartment through the fault. The calculated flux from the Eastern to the Western Compartment from *MODFLOW* is about three times higher than that from *FEMFLOW3D*. It should be noted that the flux through the fault calculated by *FEMFLOW3D* is within its model precision - difference between the calculated inflow and outflow. Table 3 shows that the differences between calculated inflow and outflow are 0.04 cfs and 0.00 cfs for *FEMFLOW3D* and *MODFLOW*, respectively.

Results of Transient Simulations

Figures 7, 8, and 9 are contour plots showing the calculated hydraulic heads at the water table, at the 1,666 ft level, and at the 375 ft level, respectively, by both *FEMFLOW3D* and *MODFLOW* for the contrived two-compartment problem under transient conditions -- specifically at the end of 20 years of pumping. These figures demonstrate that the low permeability fault has prevented the pumping stress in the "pumping center" of the Western Compartment from propagating into the Eastern Compartment in both models. The effect of the low permeability fault is also clearly illustrated by the drawdown contour in Figure 10. The magnitude and extent of the drawdown in the Eastern Compartment is much smaller than that in the Western Compartment.

As described in HCI (2006c), which describes the results of the contrived ground-water flow problem for a single compartment, there was a difference in the calculated water tables within a radius of about 15,000 ft from the "pumping center". This difference is also observed in Figures 7 and 10. As shown in Figure 7, there is a difference in the calculated water tables in the Western Compartment -- by about half a contour interval or 25 ft -- within a radius of about 30,000 ft from the pumping well with *MODFLOW* producing the higher levels. As indicated in Figure 10, this difference is also noticeable when plotted in terms of drawdown at the water table (i.e., the difference in elevations of the water table between steady-state conditions and after 20 years of pumping). Consistent with the situation shown in Figure 7, *FEMFLOW3D* calculates more drawdown than *MODFLOW* in the model layer that contains the water table in the Western Compartment. The contours in Figure 10 also indicate that *MODFLOW* shows more "sensitivity" to the effect of recharge along the two line sources in the Western Compartment, and slightly more drawdown in the Eastern Compartment.

Figures 11, 12, and 13 are contour plots showing the calculated hydraulic heads at the water table, at the 1,666 ft level, and at the 375 ft level from both models at the end of 60 years of recovery. Again, the results are essentially identical for both models.

Figures 14, 15, and 16 are hydrographs of the calculated hydraulic heads at three specific points (see Figure 2):

Point A - at a relatively low elevation within the Western Compartment,

Point B - on the central divide at the location of the pumping well, and

Point C - at a relatively high elevation within the eastern basin,

respectively.

Each of these three figures compares the calculated heads at the water table, at the 1,666 ft level, and at the 375 ft level. As shown in Figure 14, *MODFLOW* calculates a hydraulic head at the water table that is about 20 ft higher (maximum) than that calculated by *FEMFLOW3D* during the pumping period at Point A. There is also a time difference of about 2.5 years between when *FEMFLOW3D* (about 22 years) and *MODFLOW* (about 24.5 years) calculated the maximum drawdown.

As shown in Figure 15, the calculated heads in the pumping well (Point B) are similar at depth for both models. Because the wetting/re-wetting algorithm in *MODFLOW* produced irregular recovery head at the water table for the cell that contains the pumping well during approximately the first 10 years after the well is turned off, the head from the cell below the water table was used in Figure 15 to represent the recovery head at the water table for that period.

Figure 16 shows the calculated hydraulic heads with time at Point C. Because of the presence of the low permeability fault, the hydraulic heads at Point C in the Eastern Compartment show very little changes, with the heads from *MODFLOW* model showing larger decrease than that from *FEMFLOW3D*.

Figure 17 shows the calculated inter-basin flux through the low permeability fault from the Eastern Compartment to the Western Compartment. Again, the calculated flux from *MODFLOW* is about three times higher than that from *FEMFLOW3D*. The maximum inter-basin flux across the fault is about four percent and one percent of the pumping rate for *MODFLOW* and *FEMFLOW3D*, respectively.

Figure 18 shows the calculated streamflows at two points, the midpoint and the endpoint of the East and West Streams (Figure 2). Both models show the gaining nature of the West Stream and the effects of pumping on decreasing streamflow over relatively long periods of time. Both models also show the insignificant change of streamflow in the East Stream.

Finally, Figure 19 graphically depicts the components of the water budget calculated by each model through time. This includes fluxes from the constant head nodes, changes in storage, recharge, pumping discharge, ET fluxes, and the total streamflows (which are baseflows from ground water because we have not simulated direct precipitation or runoff to the streams) through time. As previously noted in Table 3, both models calculate essentially identical water budget components.

Figure 19 also shows the residual differences between the calculated inflow and outflow from both models. Both models show that the differences between the inflow and outflow are less than one percent of the total inflow (or outflow). Comparison between Figure 17 and Figure 19 illustrates that, in *FEMFLOW3D* model, the calculated flux through the fault (Figure 17) is within its model precision (differences between the inflow and outflow).

Sensitivity of *MODFLOW* Results to Hydraulic Conductivity of *HFB*

A further comparison between *MODFLOW* and *FEMFLOW3D* was conducted by changing the hydraulic conductivity value of *HFB* in *MODFLOW* (from 1×10^{-7} to 2.8×10^{-8} ft/day) to match the flux through the *HFB* in *MODFLOW* with the flux through the low permeability fault in *FEMFLOW3D* under-steady state conditions. As shown in Table 3, the flux from the Eastern to the Western Compartment is identical for both models with the reduced hydraulic conductivity value of HFB. The other water budget components in Table 3 are not sensitive to the decreased hydraulic conductivity value of *HFB*.

Figure 20 shows that, by decreasing the hydraulic conductivity of *HFB*, the transient flux through the *HFB* in *MODFLOW* is in close agreement with that from *FEMFLOW3D*.

Water levels at Observation Points A and B, as shown in Figures 21 and 22, are not sensitive to the decreased hydraulic conductivity value of *HFB* in *MODFLOW*. Water levels at Observation Point C from *MODFLOW* basically show no response to the pumping when the hydraulic conductivity value of *HFB* was assigned with 2.8 x 10^{-8} ft/day (Figure 23). In comparison, when hydraulic conductivity value of *HFB* is 1 x 10^{-7} ft/day, water levels at Observation Point C from *MODFLOW* show a slight decrease in response to the pumping (Figure 16).

CONCLUSIONS

Based on our comparison of the results derived from *FEMFLOW3D* and *MODFLOW* for the contrived two-compartment ground-water flow problem, HCI concludes -- assuming that the public domain code *MODFLOW* and its *HFB* routine produce a "correct" solution -- the following:

1) In order to obtain the same flux through the low permeability fault for both models, the hydraulic conductivity for *HFB* in *MODFLOW* needs to be lower than that calculated from the transverse leakance factor in *FEMFLOW3D*;

2) *FEMFLOW3D* properly calculates hydraulic heads and water budgets under steady-state conditions with a low permeability fault in the model domain; and

3) *FEMFLOW3D* properly calculates hydraulic heads and water budgets under transient conditions (simulated by a pumping stress of finite duration) with a low permeability fault in the model domain.

As for the differences between the elevations of the water table calculated by the two codes, HCI has pointed it out and requested comments from the author in our previous memorandum (HCI, 2006c).

CLOSURE

Please contact us if you have any questions regarding any of the findings in this Technical Memorandum.

REFERENCES

Hydrologic Consultants, Inc., 2006a, Preliminary comments on *FEMFLOW3D* documentation: Technical Memorandum submitted to SNWA, May 5.

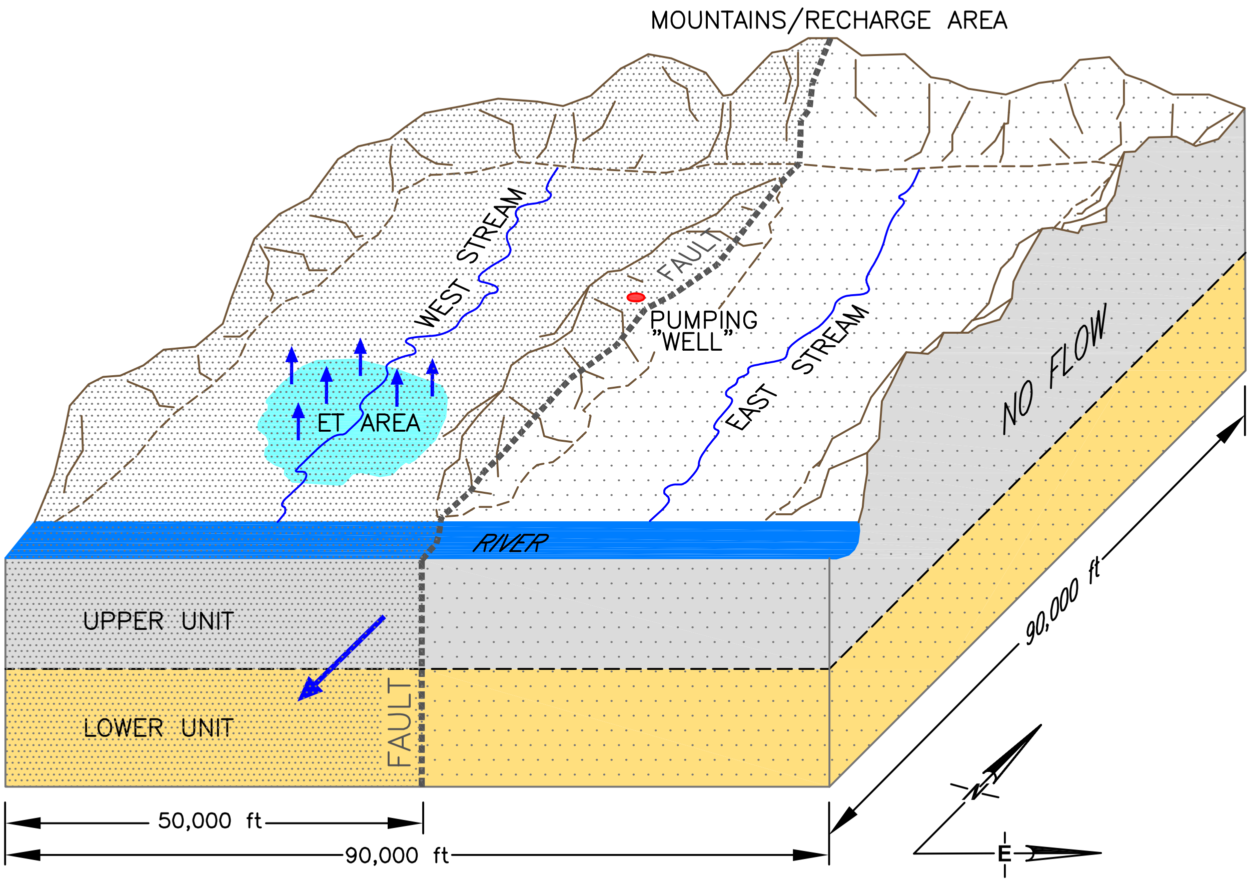
Hydrologic Consultants, Inc., 2006b, Additional comments on *FEMFLOW3D* documentation and review of the source code: Technical Memorandum submitted to SNWA, June 5.

Hydrologic Consultants, Inc., 2006b, Comparison between calculations by *FEMFLOW3D* and *MODFLOW* for contrived, single compartment ground-water flow problem: Technical Memorandum submitted to SNWA, June 14.

Hydrologic Consultants, Inc., 2006d, Revised scope of work and cost estimate - review of *FEMFLOW3D* ground-water flow code: submitted to SNWA, April 19.

Attachments:
- Figure 1 - Schematic Diagram of Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 2 - Boundary Conditions and Features of Numerical Models for Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 3 - Model Meshes and Boundary Conditions for Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 4 - Calculated Water Tables under Steady-State Conditions for Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 5 - Calculated Hydraulic Heads at Elevation 1,666 ft under Steady-State Conditions for Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 6 - Calculated Hydraulic Heads at Elevation 375 ft under Steady-State Conditions for Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 7 - Calculated Water Tables after 20 Years of Pumping for Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 8 - Calculated Hydraulic Heads at Elevation 1,666 ft after 20 Years of Pumping for Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 9 - Calculated Hydraulic Heads at Elevation 375 ft after 20 Years of Pumping for Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 10 - Calculated Drawdown of Water Table after 20 Years of Pumping for Contrived Two-Compartment Problem with Low Permeability Fault
- Figure 11 - Calculated Water Table after 60 Years of Recovery for Contrived

Two-Compartment Problem with Low Permeability Fault
Figure 12 - Calculated Hydraulic Heads at Elevation 1,666 ft after 60 Years of Recovery for Contrived Two-Compartment Problem with Low Permeability Fault
Figure 13 - Calculated Hydraulic Heads at Elevation 375 ft after 60 years of Recovery for Contrived Two-Compartment Problem with Low Permeability Fault
Figure 14 - Hydrographs of Calculated Hydraulic Heads at Point A at Three Different Elevations
Figure 15 - Hydrographs of Calculated Hydraulic Heads at Point B (Pumping Well) at Three Different Elevations
Figure 16 - Hydrographs of Calculated Hydraulic Heads at Point C at Three Different Elevations
Figure 17 - Calculated Flux from Eastern Compartment to Western Compartment through Low Permeability Fault for Contrived Two-Compartment Problem
Figure 18 - Calculated Streamflows at Midpoints and Endpoints of Streams
Figure 19 - Calculated Water Budgets
Figure 20 - Calculated Flux from Eastern Compartment to Western Compartment through Low Permeability Fault Using Different K Values of *HFB*
Figure 21 - Hydrographs of Calculated Hydraulic Heads at Point A at Three Different Elevations Using Different K Values of *HFB*
Figure 22 - Hydrographs of Calculated Hydraulic Heads at Point B (Pumping Well) at Three Different Elevations Using Different K Values of *HFB*
Figure 23 - Hydrographs of Calculated Hydraulic Heads at Point C at Three Different Elevations Using Different K Values of *HFB*
Table 1 - Hydraulic Properties of Hydrostratigraphic Units used in Contrived Problem
Table 2 - Locations and Specified Elevations of Stream Nodes
Table 3 - Calculated Water Budgets under Steady-State Conditions



EXPLANATION

WESTERN COMPARTMENT

EASTERN COMPARTMENT

NOT TO SCALE

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Schematic Diagram of Contrived Two-Compartment Problem with Low Permeability Fault

FIGURE 1

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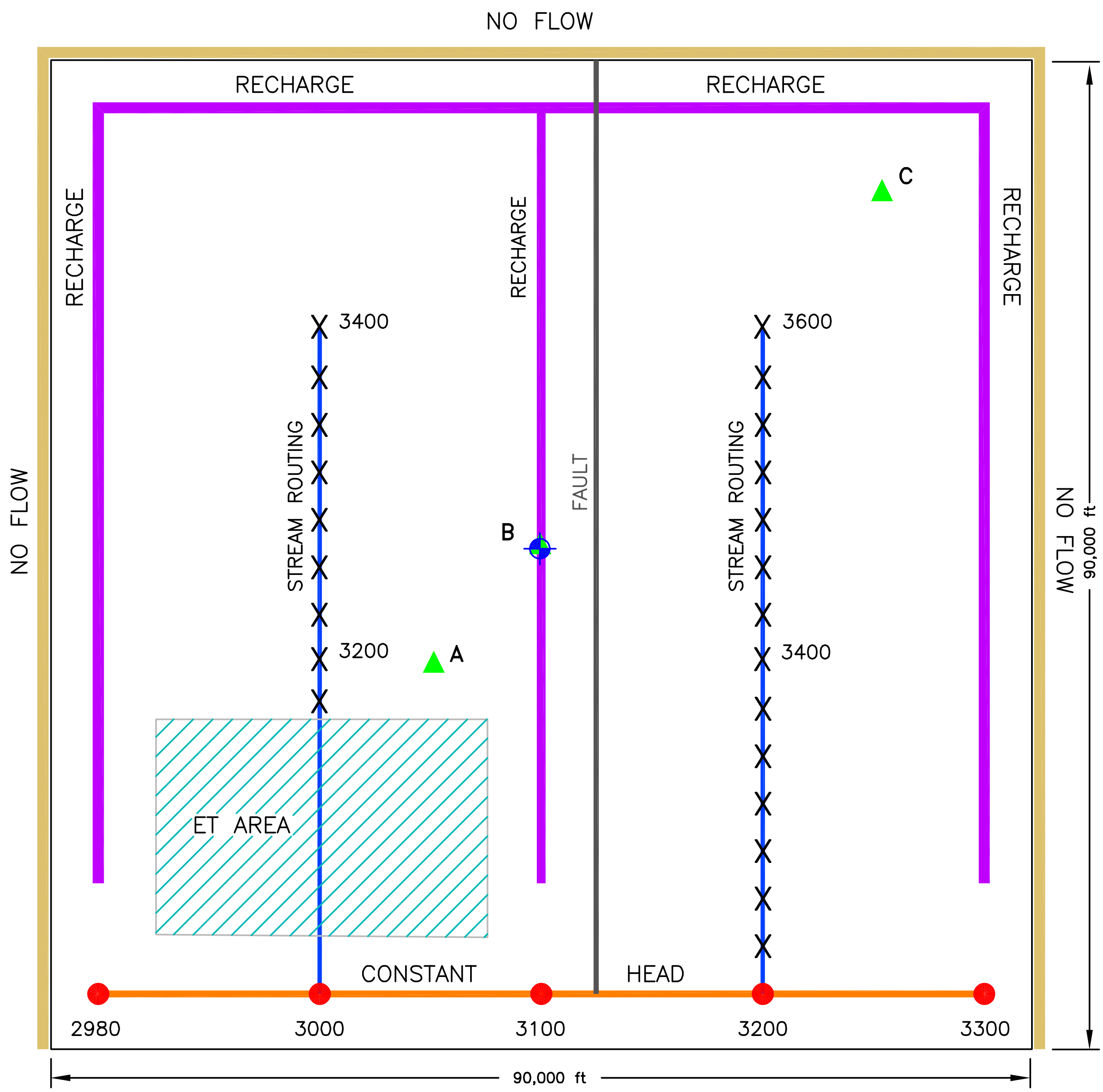

EXPLANATION

- CONSTANT HEAD NODE/CELL WITH ASSIGNED HEAD (FT)
- X STREAM NODE/CELL WITH ASSIGNED ELEVATION (FT)
- PUMPING "WELL"
- OBSERVATION POINT FOR HYDROGRAPHS

NOTE: NOT ALL NODES/CELLS SHOWN; SEE FIGURE 3

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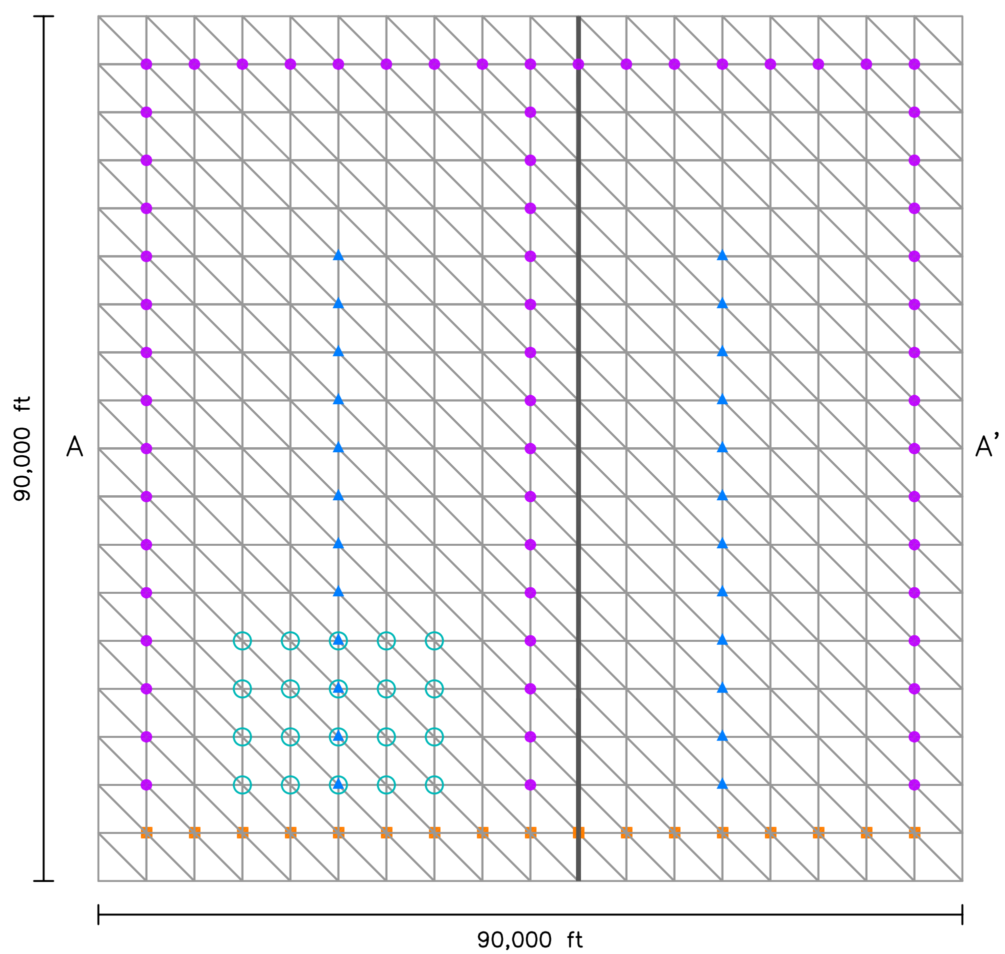
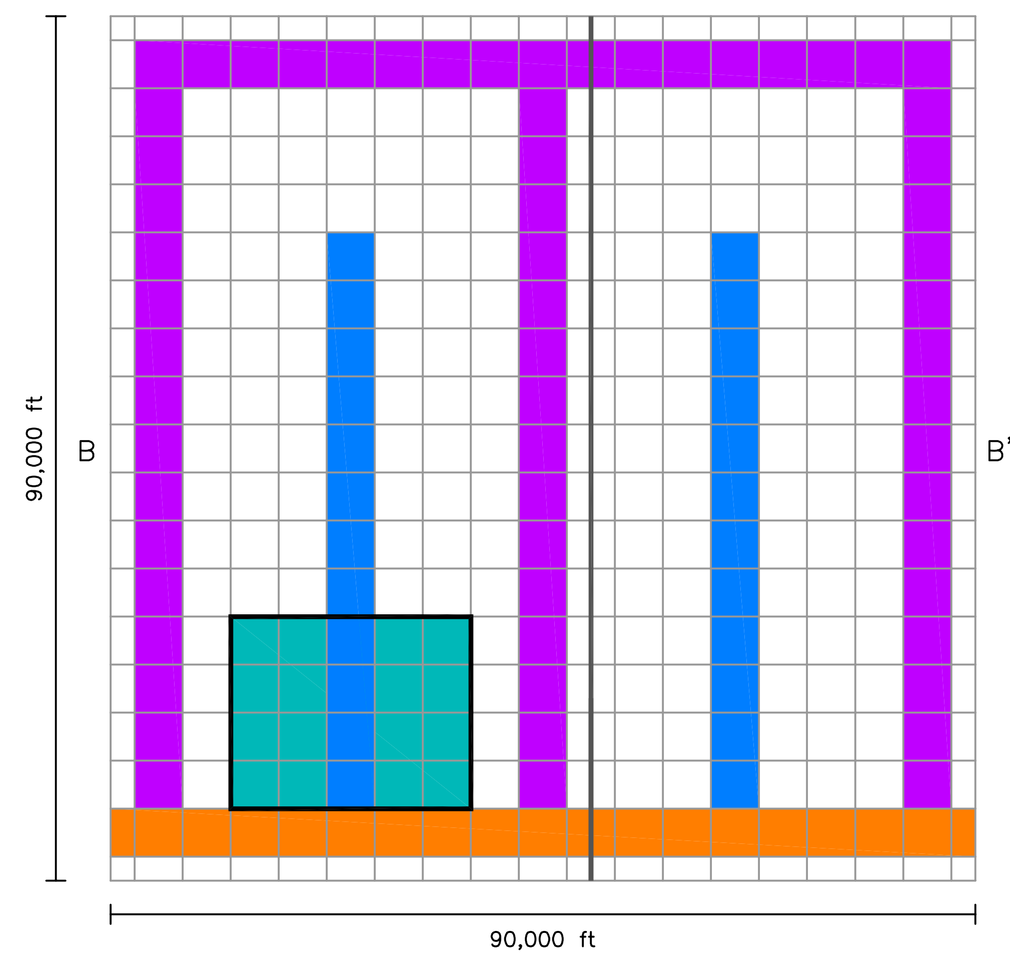
Boundary Conditions and Features of Numerical Models for Contrived Two-Compartment Problem with Low Permeability Fault

FIGURE 2

FEMFLOW3D — Section



MODFLOW — Section



EXPLANATION

FEMFLOW3D

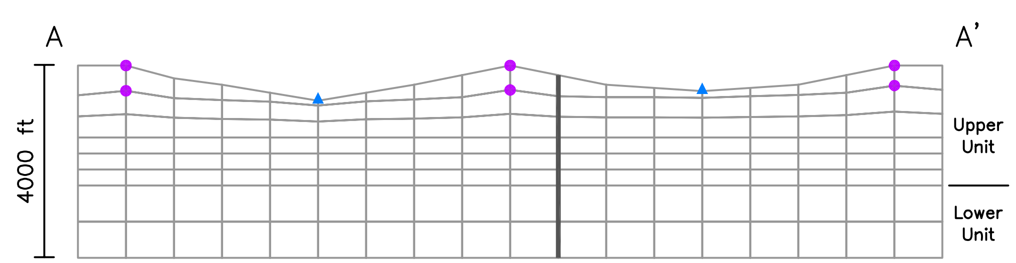
- CONSTANT HEAD
- EVAPOTRANSPIRATION
- RECHARGE FLUX (0.1917 cfs/node)
- STREAM

MODFLOW

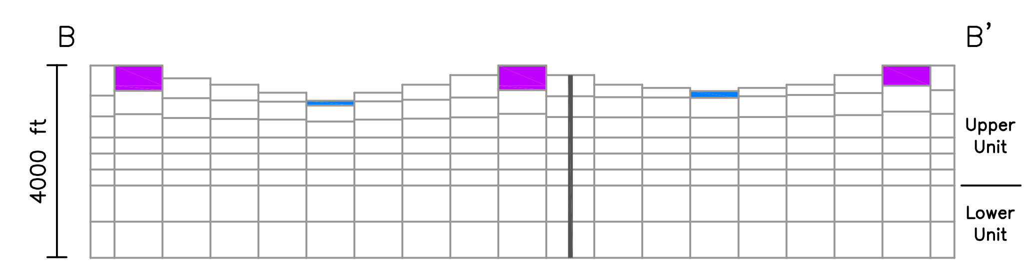
- CONSTANT HEAD
- EVAPOTRANSPIRATION
- RECHARGE RATE (0.001326 ft/day)
- STREAM

- FAULT

FEMFLOW3D — Section



MODFLOW — Section



Model Meshes and Boundary Conditions for Contrived Two-Compartment Problem with Low Permeability Fault

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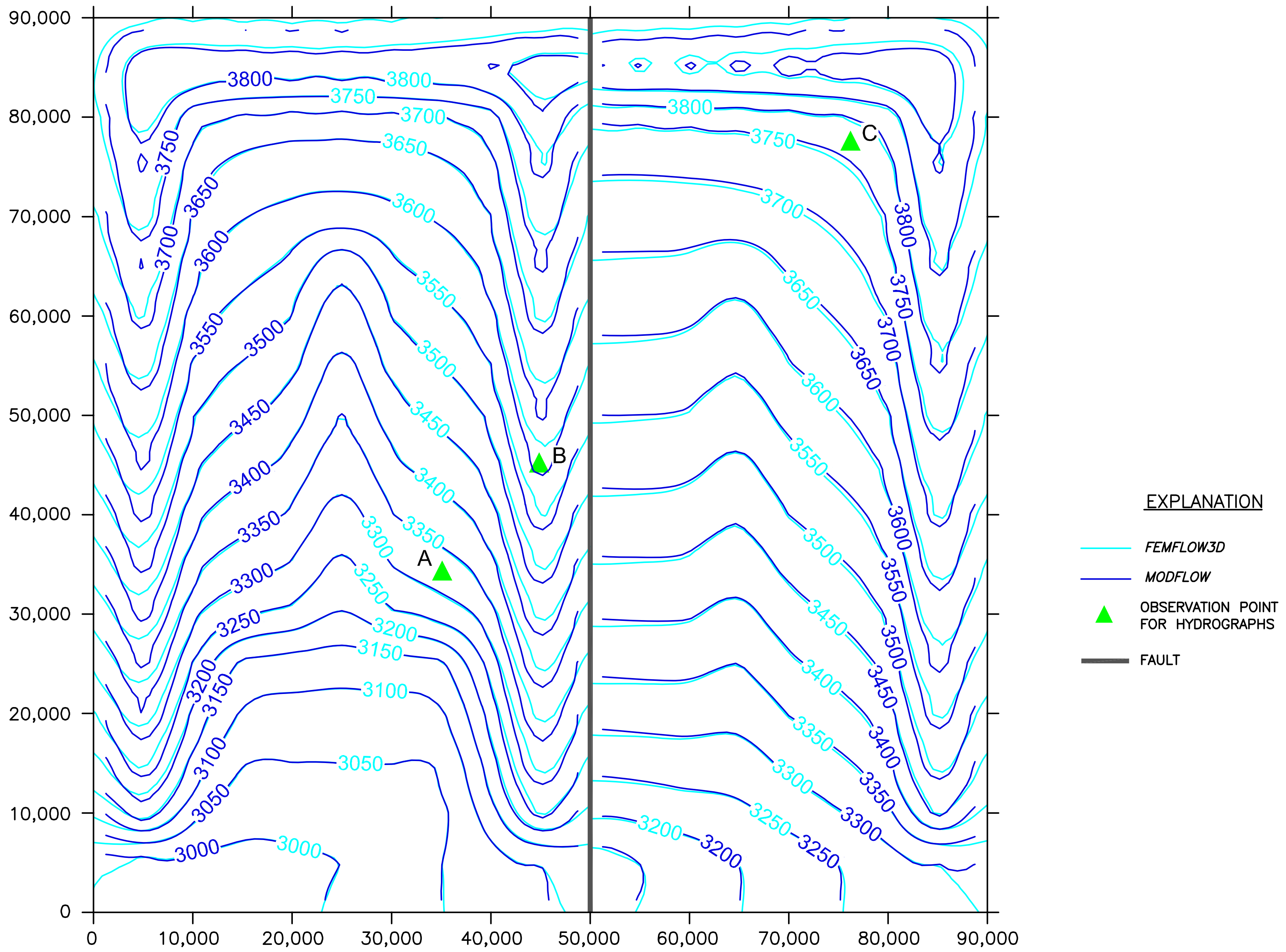
FIGURE 3



HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. HCI-1827	DATE: 25 MAY 06	**Calculated Water Tables under Steady-State Conditions for Contrived Two-Compartment Problem with Low Permeability Fault**	FIGURE 4
HC TASCA an company	BY: HL	DWG FILE: WT-ST-STATE-TM5a		
	DRAWN: SAC	PLOT FILE: WT-ST-STATE-TM5a		
	CHECKED:	PLOT DATE: 26 JUN 06		

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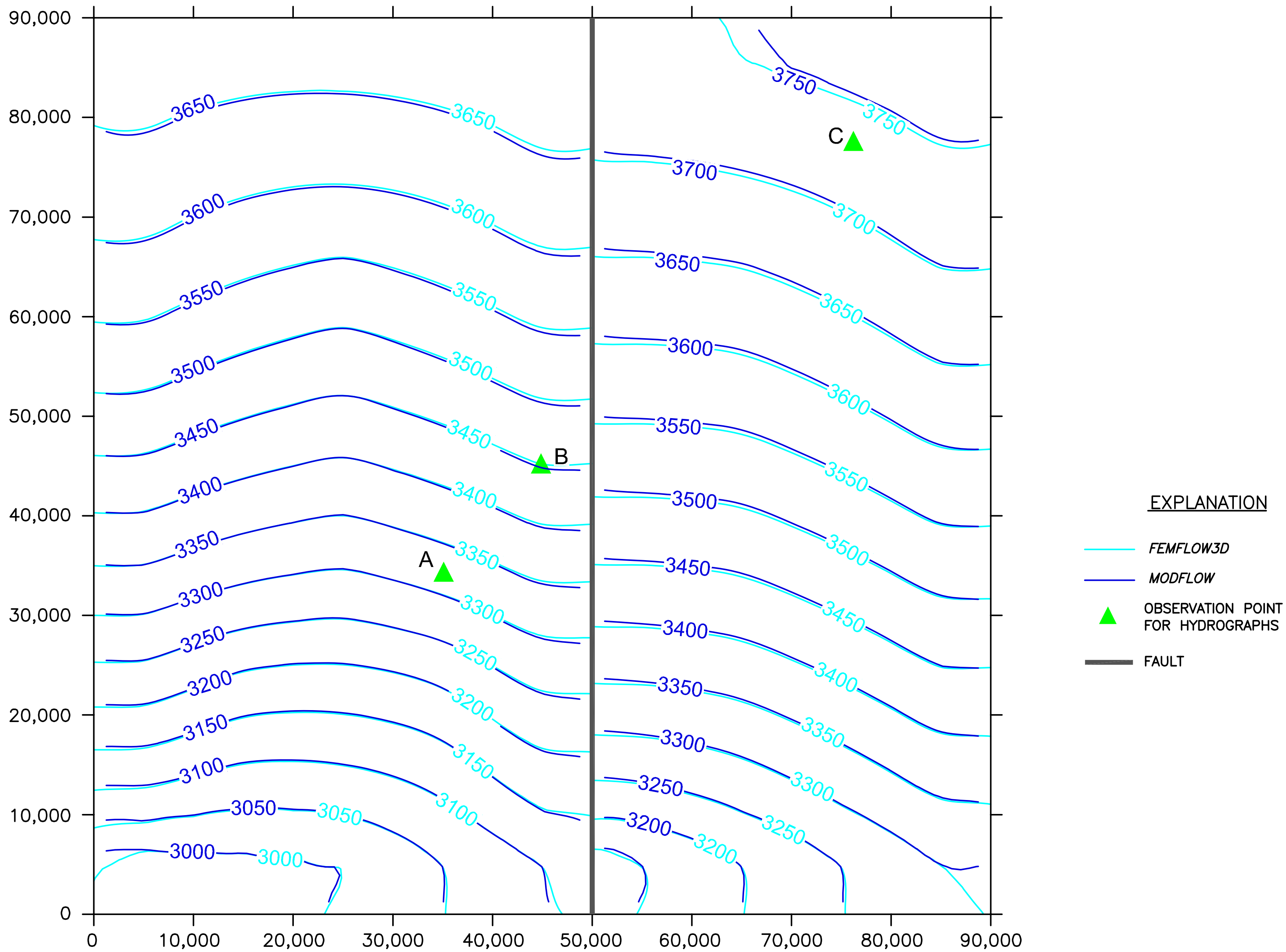
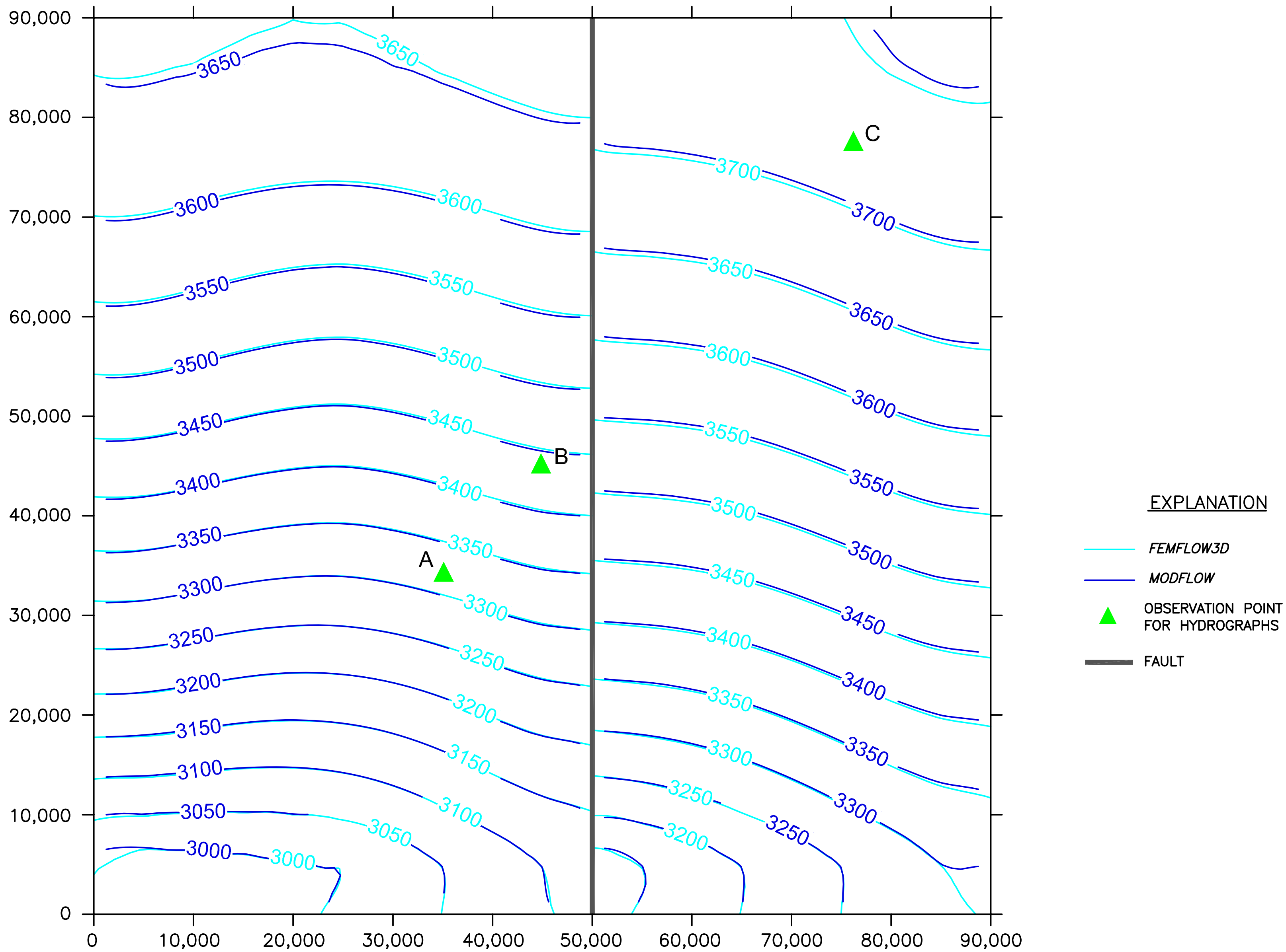


HCI HYDROLOGIC CONSULTANTS, INC. — HC ITASCA an company	JOB NO. HCI–1827	DATE: 25 MAY 06	**Calculated Hydraulic Heads at Elevation 1,666 ft Under Steady-State Conditions for Contrived Two-Compartment Problem with Low Permeability Fault**
	BY: HL	DWG FILE: HEAD-EL-1666-TM5a	FIGURE 5
	DRAWN: SAC	PLOT FILE: HEAD-EL-1666-TM5a	
	CHECKED:	PLOT DATE: 26 JUN 06	



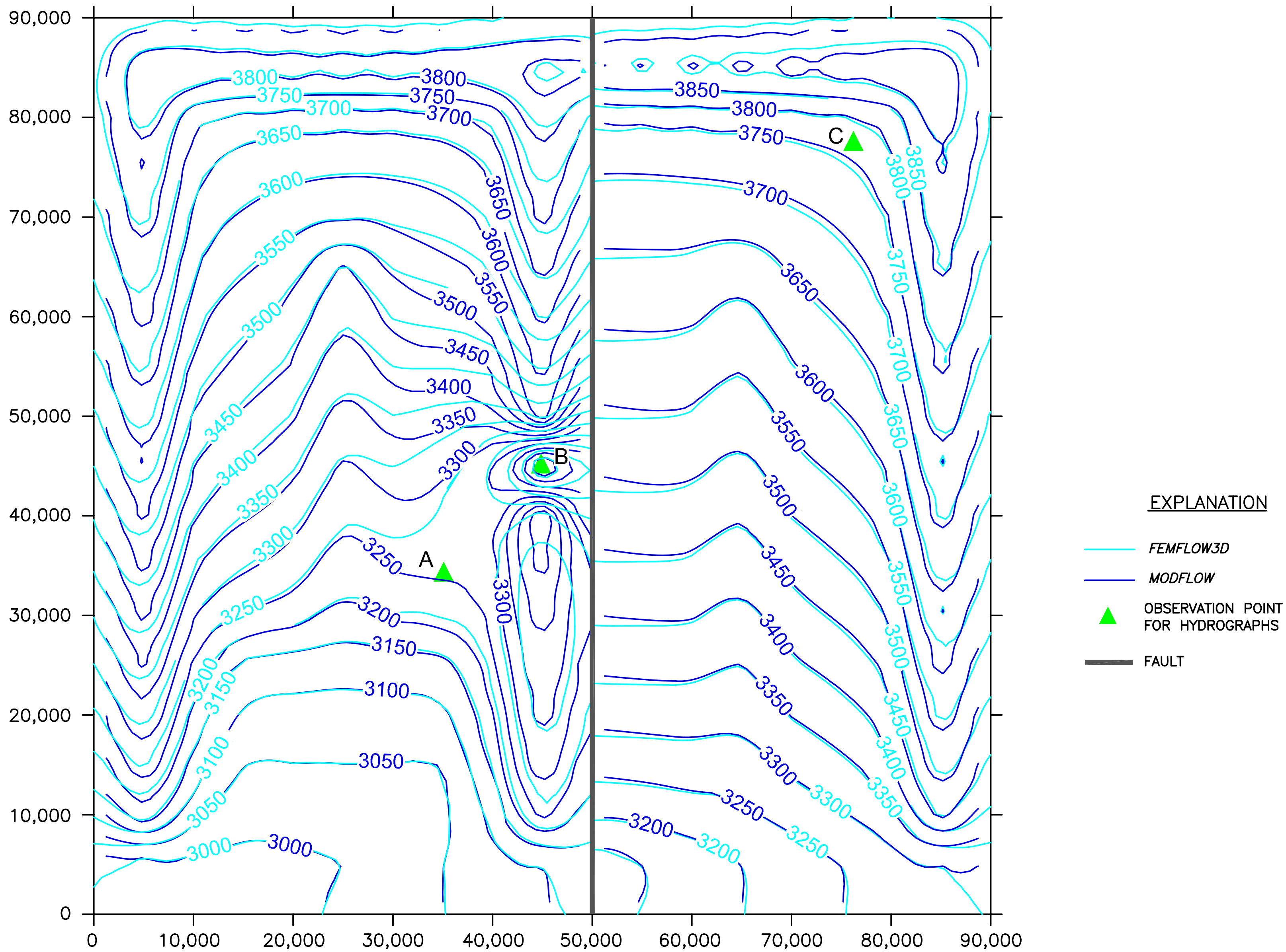
HCI HYDROLOGIC CONSULTANTS, INC.
HC TASCA an company

JOB NO. HCI–1827	DATE: 25 MAY 06
BY: HL	DWG FILE: HEAD–EL–375–TM5a
DRAWN: SAC	PLOT FILE: HEAD–EL–375–TM5a
CHECKED:	PLOT DATE: 26 JUN 06

Calculated Hydraulic Heads at Elevation 375 ft Under Steady-State Conditions for Contrived Two-Compartment Problem with Low Permeability Fault

FIGURE 6

C:\Projects\1827-SNWA\TM5\HEAD-EL-375-TM5a.dwg, 6/27/2006 2:39:20 PM



HCI HYDROLOGIC CONSULTANTS, INC. / HC TASCA an company	JOB NO. HCI–1827	DATE: 19 JUN 06	**Calculated Water Tables after 20 Years of Pumping for Contrived Two–Compartment Problem with Low Permeability Fault**	FIGURE 7
	BY: HL	DWG FILE WT–20YRS–PUMP–TM5a		
	DRAWN: SAC	PLOT FILE WT–20YRS–PUMP–TM5a		
	CHECKED:	PLOT DATE: 26 JUN 06		

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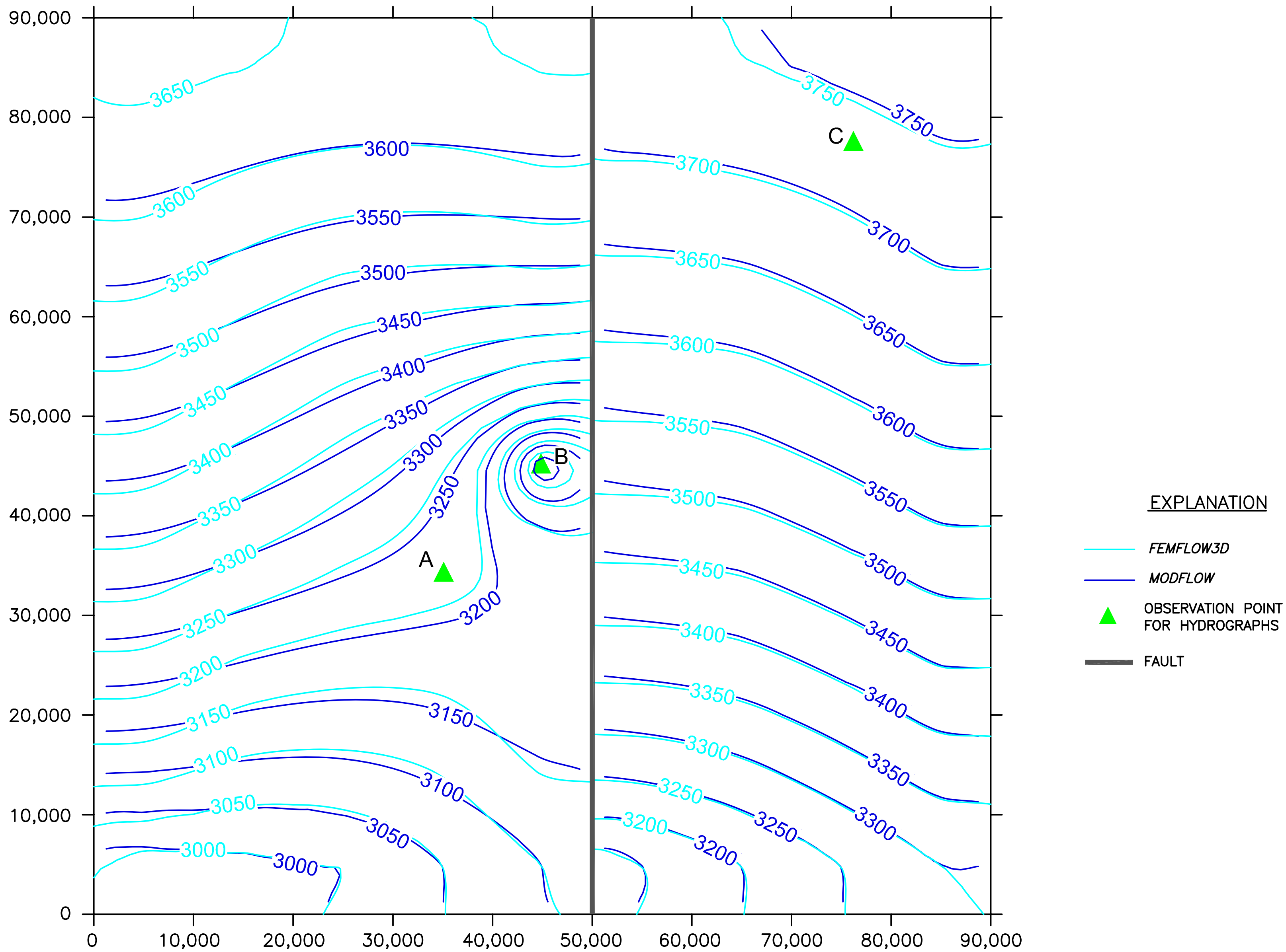

JOB NO. HCI–1827	DATE: 19 JUN 06	Calculated Hydraulic Heads at Elevation 1,666 ft after 20 Years of Pumping for Contrived Two-Compartment Problem with Low Permeability Fault	FIGURE 8
BY: HL	DWG FILE HH-1666-20YRS-TM5a		
DRAWN: SAC	PLOT FILE HH-1666-20YRS-TM5a		
CHECKED:	PLOT DATE: 26 JUN 06		

HCI HYDROLOGIC CONSULTANTS, INC. — HC ITASCA an company

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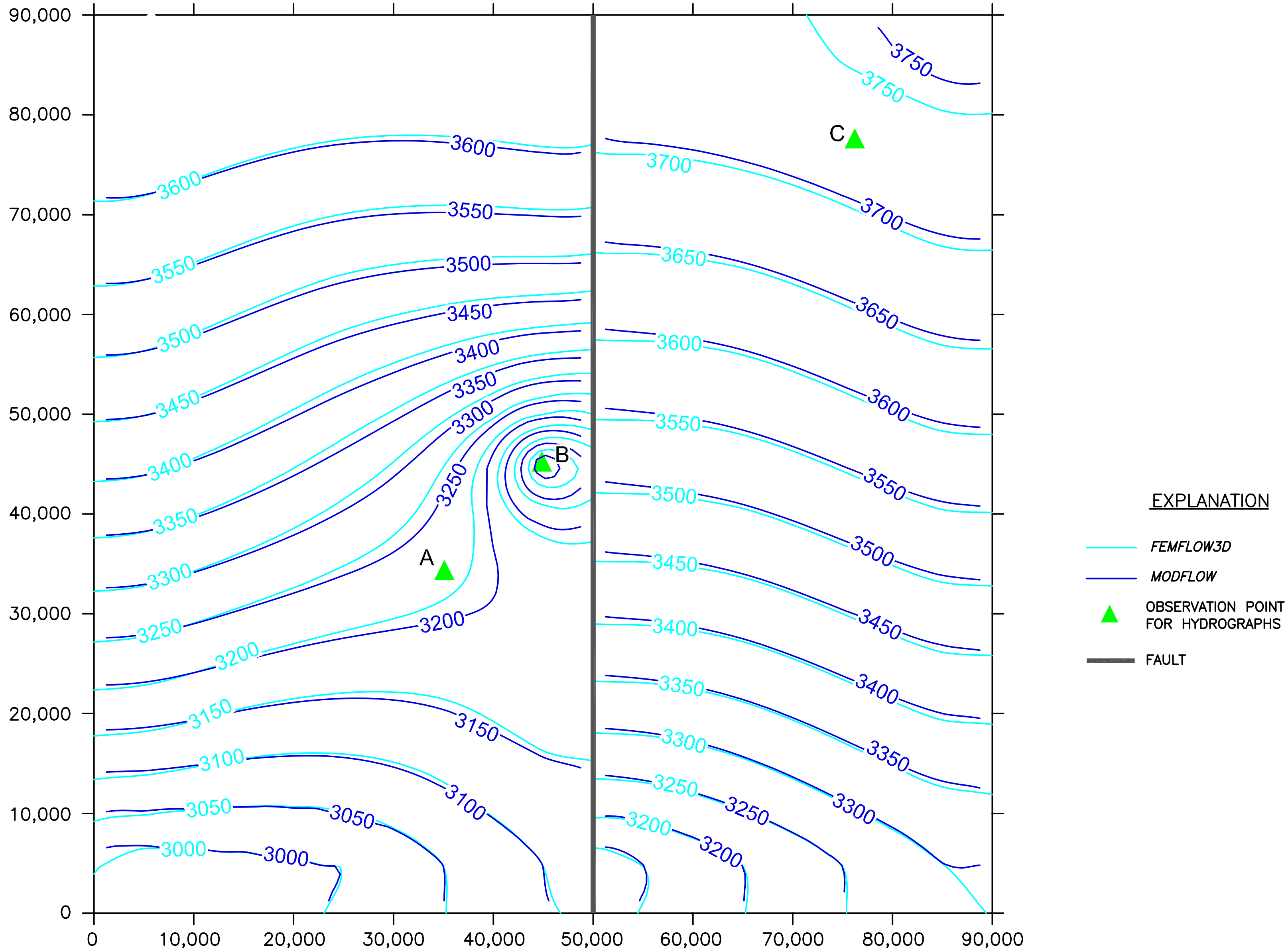

HCI HYDROLOGIC CONSULTANTS, INC. — HC TASCA an company	JOB NO. HCI–1827	DATE: 19 JUN 06	Calculated Hydraulic Heads at Elevation 375 ft after 20 Years of Pumping for Contrived Two-Compartment Problem with Low Permeability Fault	FIGURE 9
	BY: HL	DWG FILE: HH-375-20YRS-TM5a		
	DRAWN: SAC	PLOT FILE: HH-375-20YRS-TM5a		
	CHECKED:	PLOT DATE: 26 JUN 06		

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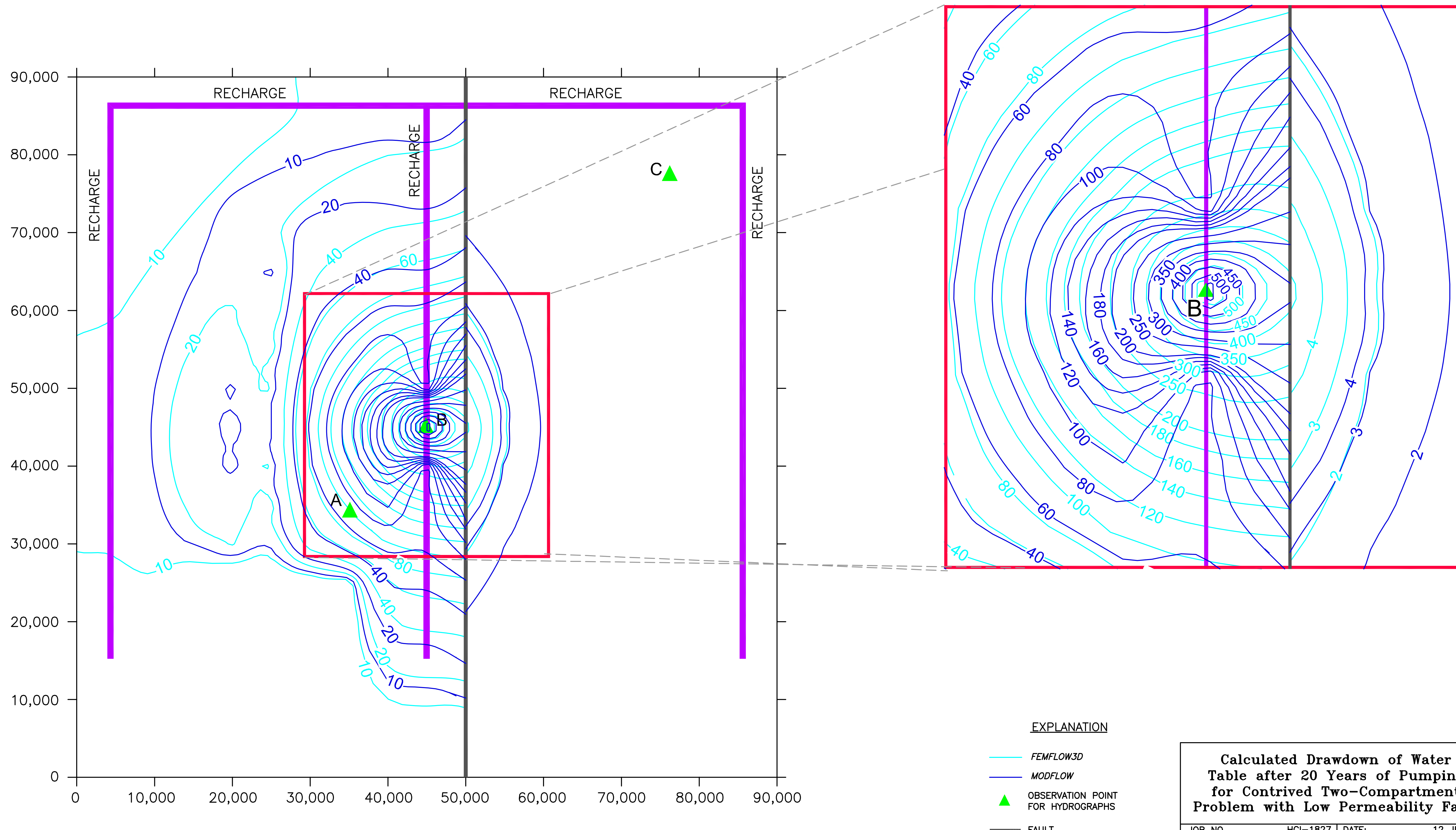
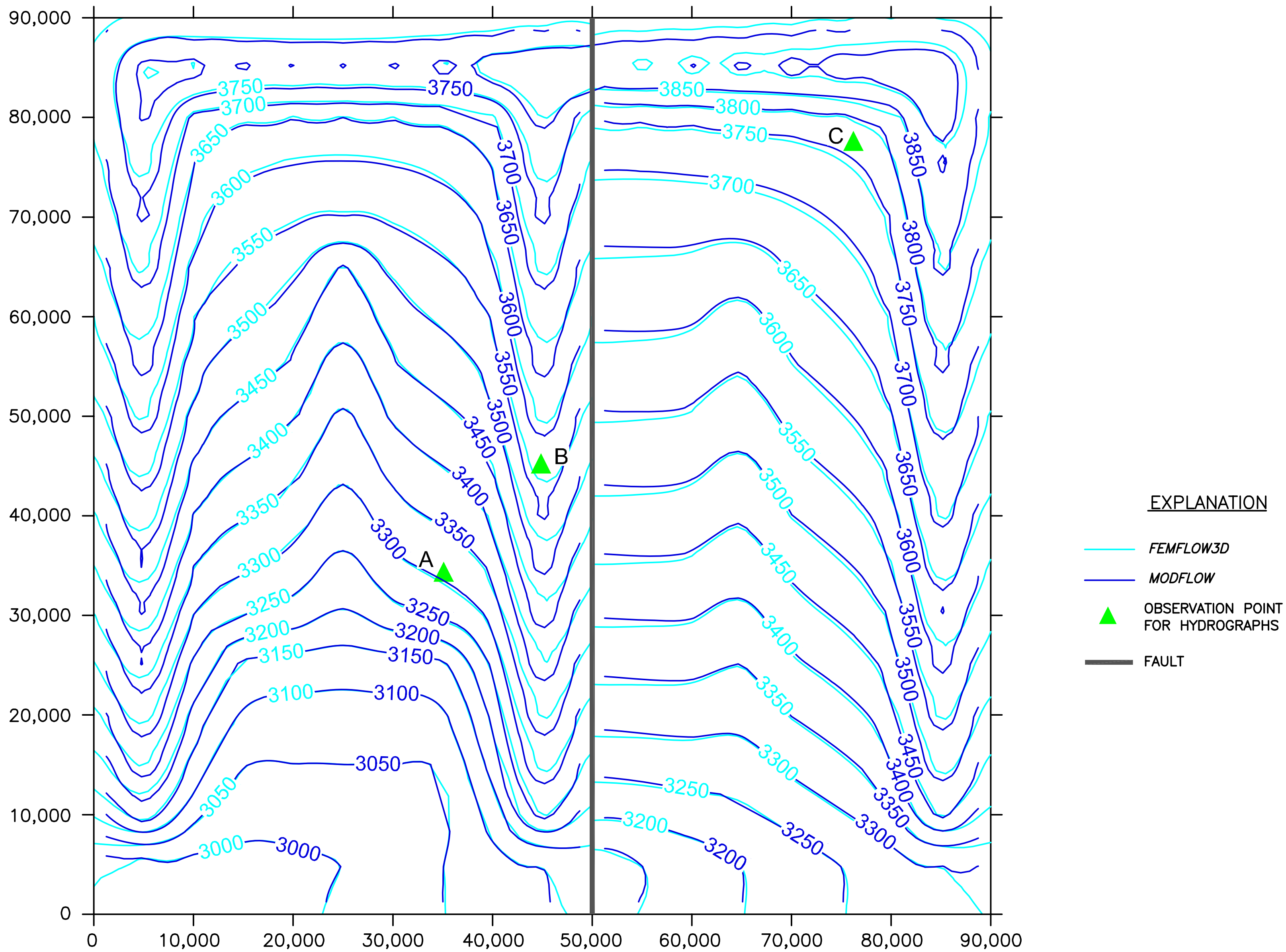


Calculated Drawdown of Water Table after 20 Years of Pumping for Contrived Two-Compartment Problem with Low Permeability Fault

JOB NO.	HCI-1827	DATE:	12 JUN 06
BY:	HL	DWG FILE:	DRAWDOWN-TM5a
DRAWN:	SAC	PLOT FILE:	DRAWDOWN-TM5a
CHECKED:		PLOT DATE:	26 JUN 06

HCI HYDROLOGIC CONSULTANTS, INC. — an HC Itasca company

FIGURE 10



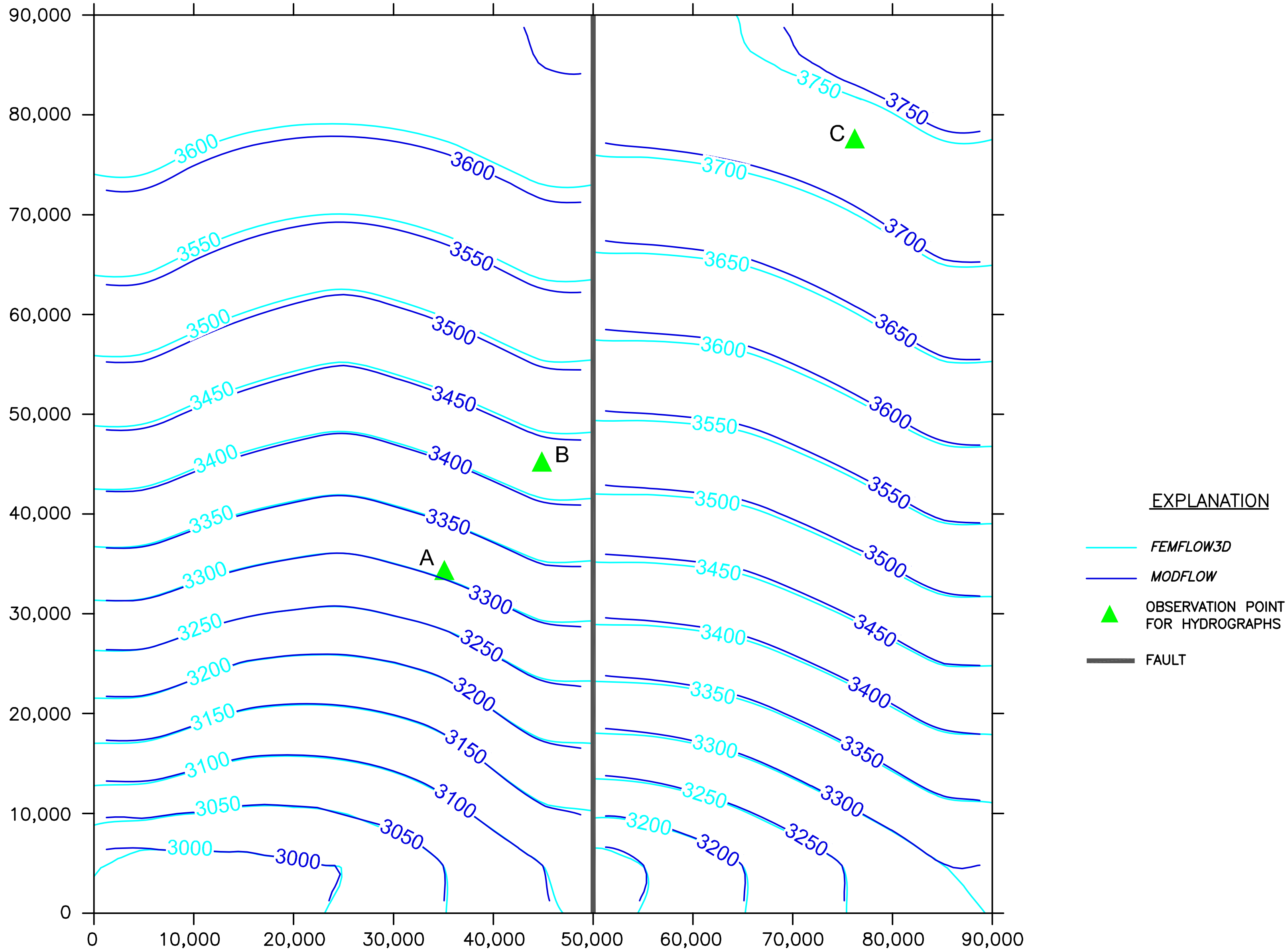
HYDROLOGIC CONSULTANTS, INC.

HC TASCA an company

JOB NO.	HCI–1827	DATE:	19 JUN 06
BY:	HL	DWG FILE:	WT–60YRS–REC–TM5a
DRAWN:	SAC	PLOT FILE:	WT–60YRS–REC–TM5a
CHECKED:		PLOT DATE:	26 JUN 06

Calculated Water Table after 60 Years of Recovery for Contrived Two–Compartment Problem with Low Permeability Fault

FIGURE 11

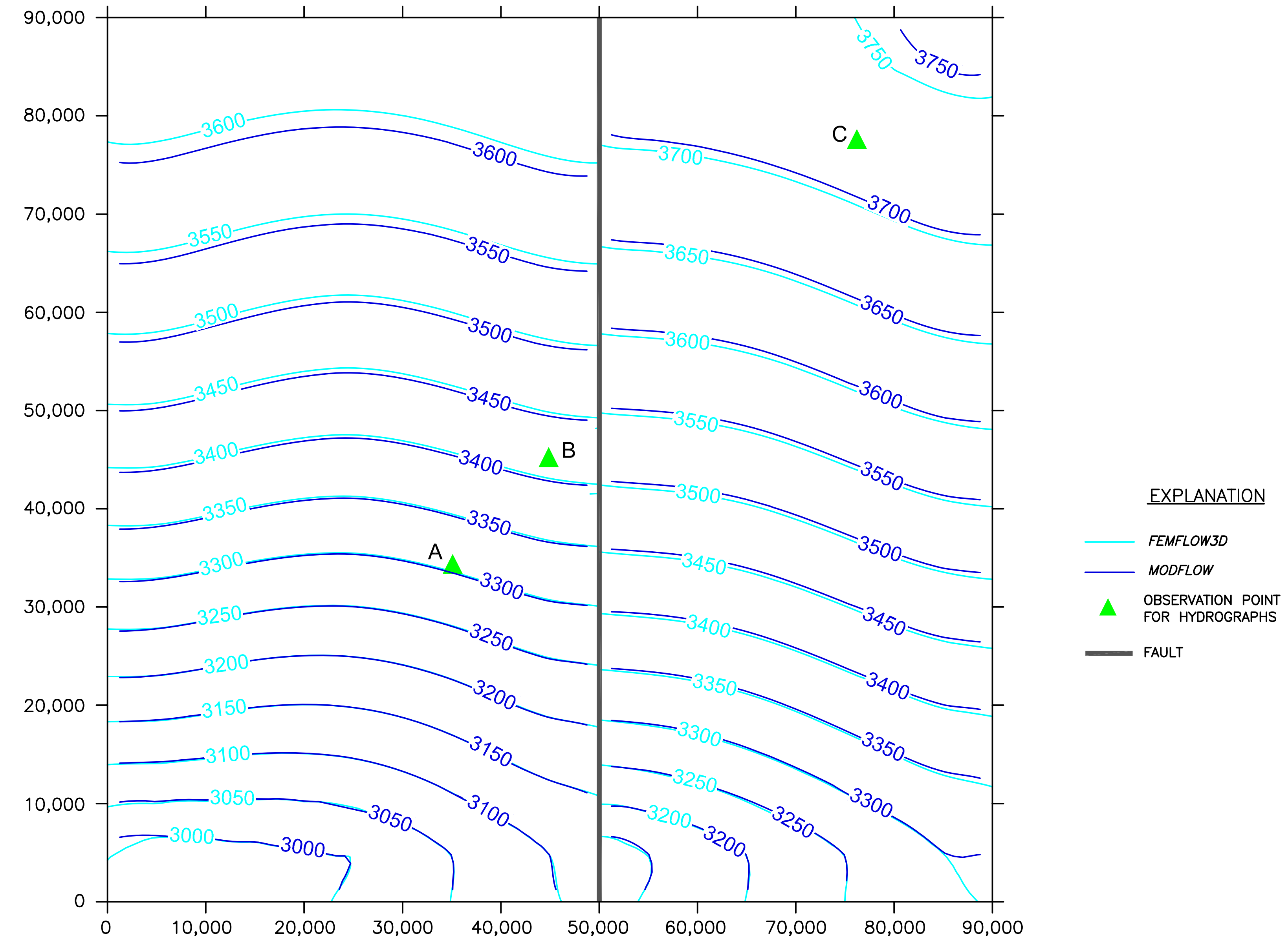


HCI HYDROLOGIC CONSULTANTS, INC.	JOB NO. HCI–1827	DATE: 19 JUN 06	
HC TASCA an company	BY: HL	DWG FILE: HEAD1666–60YRS–TM5a	
	DRAWN: SAC	PLOT FILE: HEAD1666–60YRS–TM5a	
	CHECKED:	PLOT DATE: 26 JUN 06	

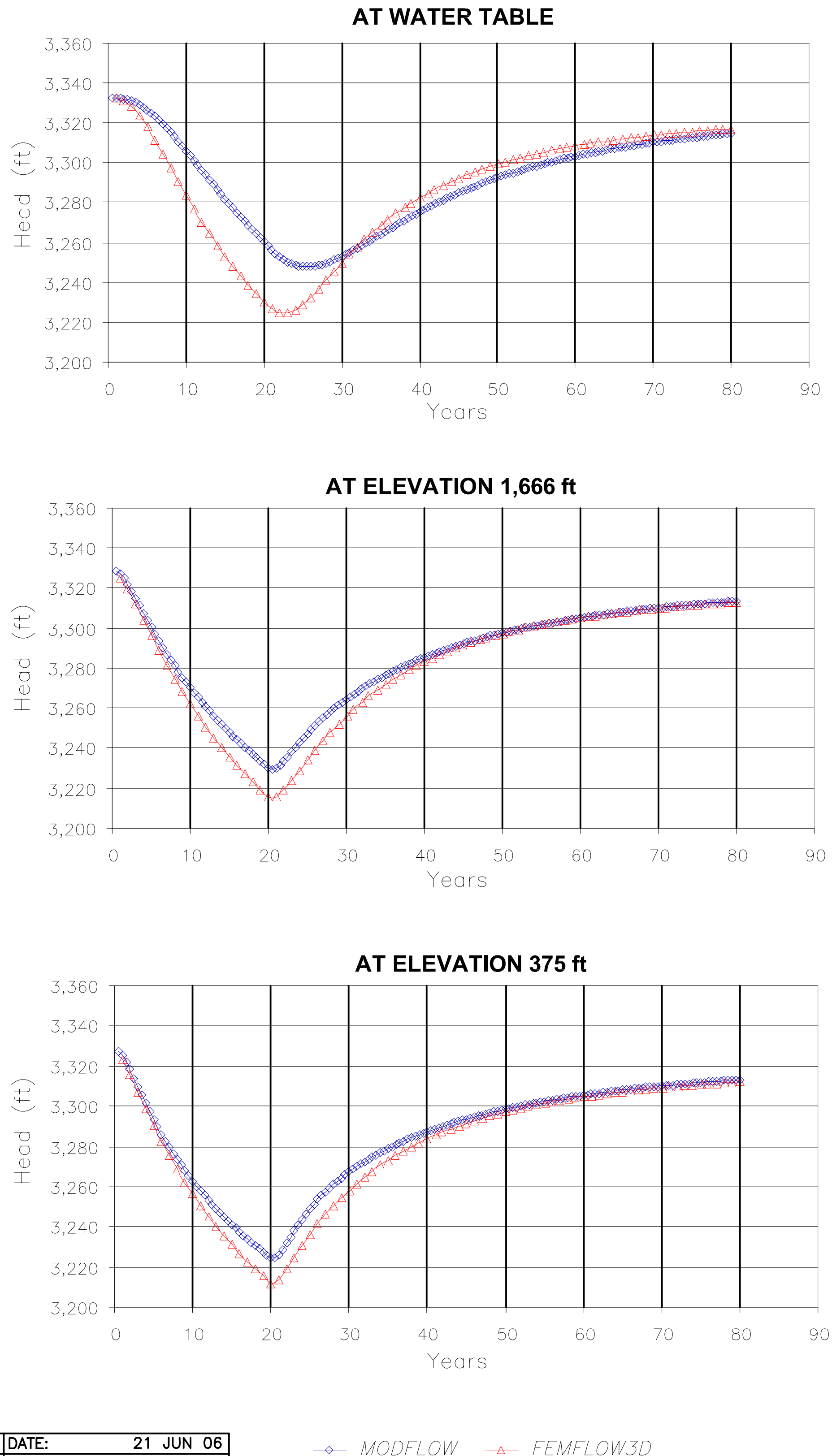
Calculated Hydraulic Heads at Elevation 1,666 ft after 60 Years of Recovery for Contrived Two-Compartment Problem with Low Permeability Fault

FIGURE 12

C:\Projects\1827–SNWA\TM5\HEAD1666–60YRS–TM5a.dwg, 6/27/2006 2:38:55 PM



HCI HYDROLOGIC CONSULTANTS, INC. / HC TASCA an company	JOB NO. HCI-1827	DATE: 19 JUN 06	Calculated Hydraulic Heads at Elevation 375 ft after 60 Years of Recovery for Contrived Two-Compartment Problem with Low Permeability Fault	FIGURE 13
	BY: HL	DWG FILE: HEAD375-60YRS-TM5a		
	DRAWN: SAC	PLOT FILE: HEAD375-60YRS-TM5a		
	CHECKED:	PLOT DATE: 26 JUN 06		



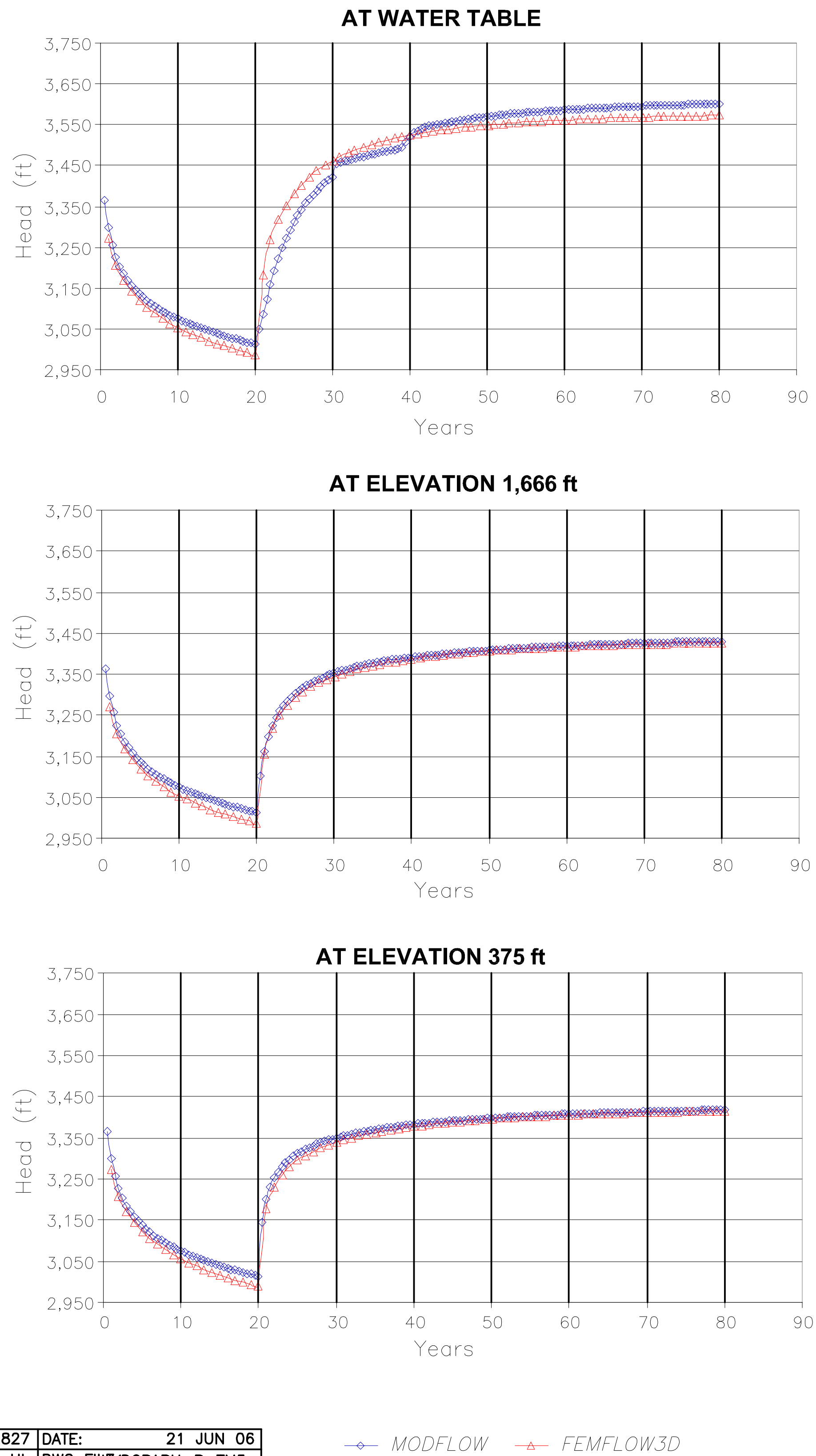
JOB NO.	HCI–1827	DATE:	21 JUN 06
BY:	HL	DWG FILE:	HYDGRAPH–A–TM5a
DRAWN:	SAC	PLOT FILE:	HYDGRAPH–A–TM5a
CHECKED:		PLOT DATE:	26 JUN 06

HCI HYDROLOGIC CONSULTANTS, INC.

HC | TASCA an company

Hydrographs of Calculated Hydraulic Heads at Point A at Three Different Elevations

FIGURE 14



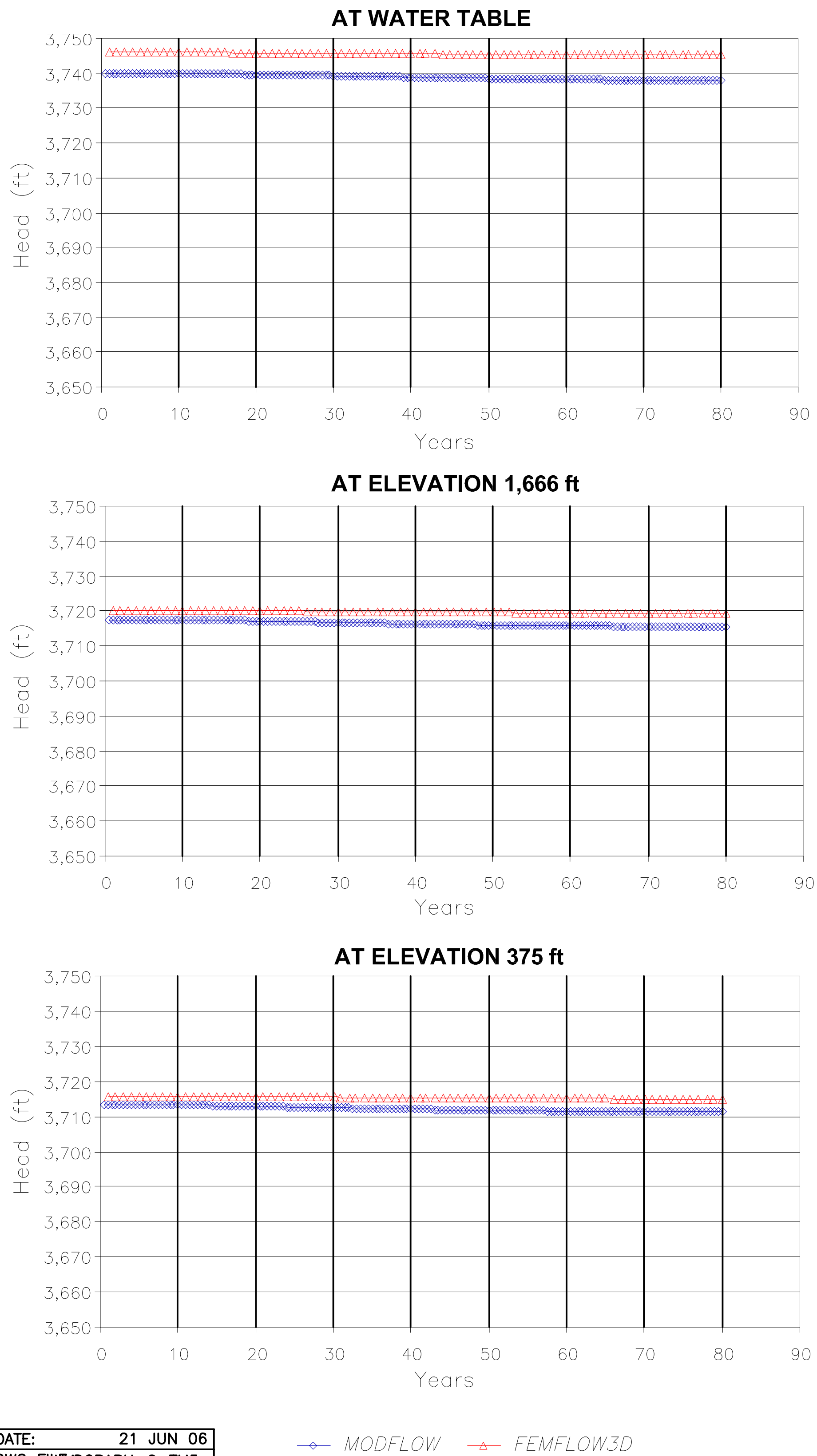
JOB NO.	HCI–1827	DATE:	21 JUN 06
BY:	HL	DWG FILE:	HYDGRAPH–B–TM5a
DRAWN:	SAC	PLOT FILE:	HYDGRAPH–B–TM5a
CHECKED:		PLOT DATE:	26 JUN 06

HCI HYDROLOGIC CONSULTANTS, INC.

HC | TASCA an company

Hydrographs of Calculated Hydraulic Heads at Point B (Pumping Well) at Three Different Elevations

FIGURE 15



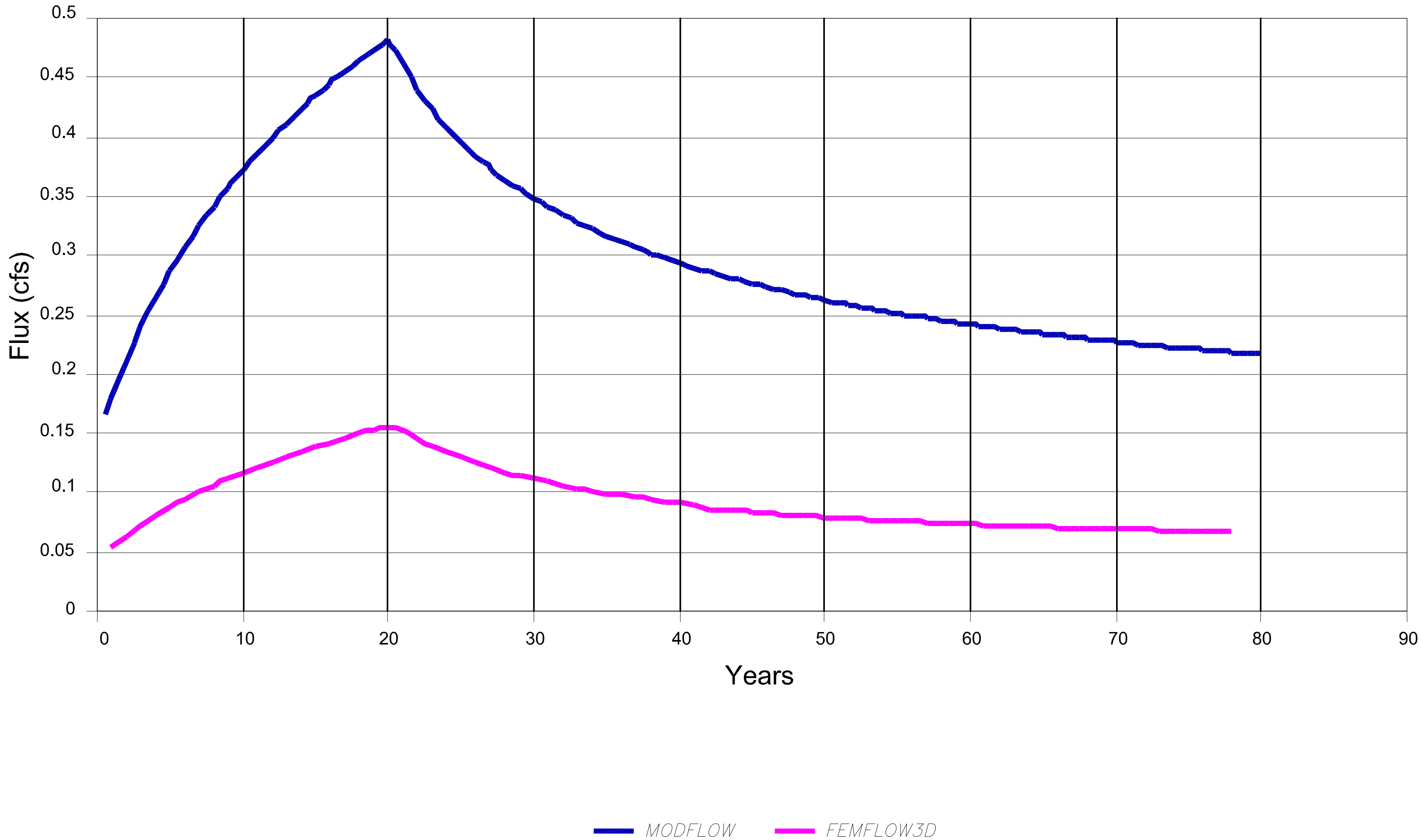
JOB NO.	HCI–1827	DATE:	21 JUN 06
BY:	HL	DWG FILE:	HYDGRAPH–C–TM5a
DRAWN:	SAC	PLOT FILE:	HYDGRAPH–C–TM5a
CHECKED:		PLOT DATE:	26 JUN 06

HCI HYDROLOGIC CONSULTANTS, INC.

HC | TASCA an company

Hydrographs of Calculated Hydraulic Heads at Point C at Three Different Elevations

FIGURE 16

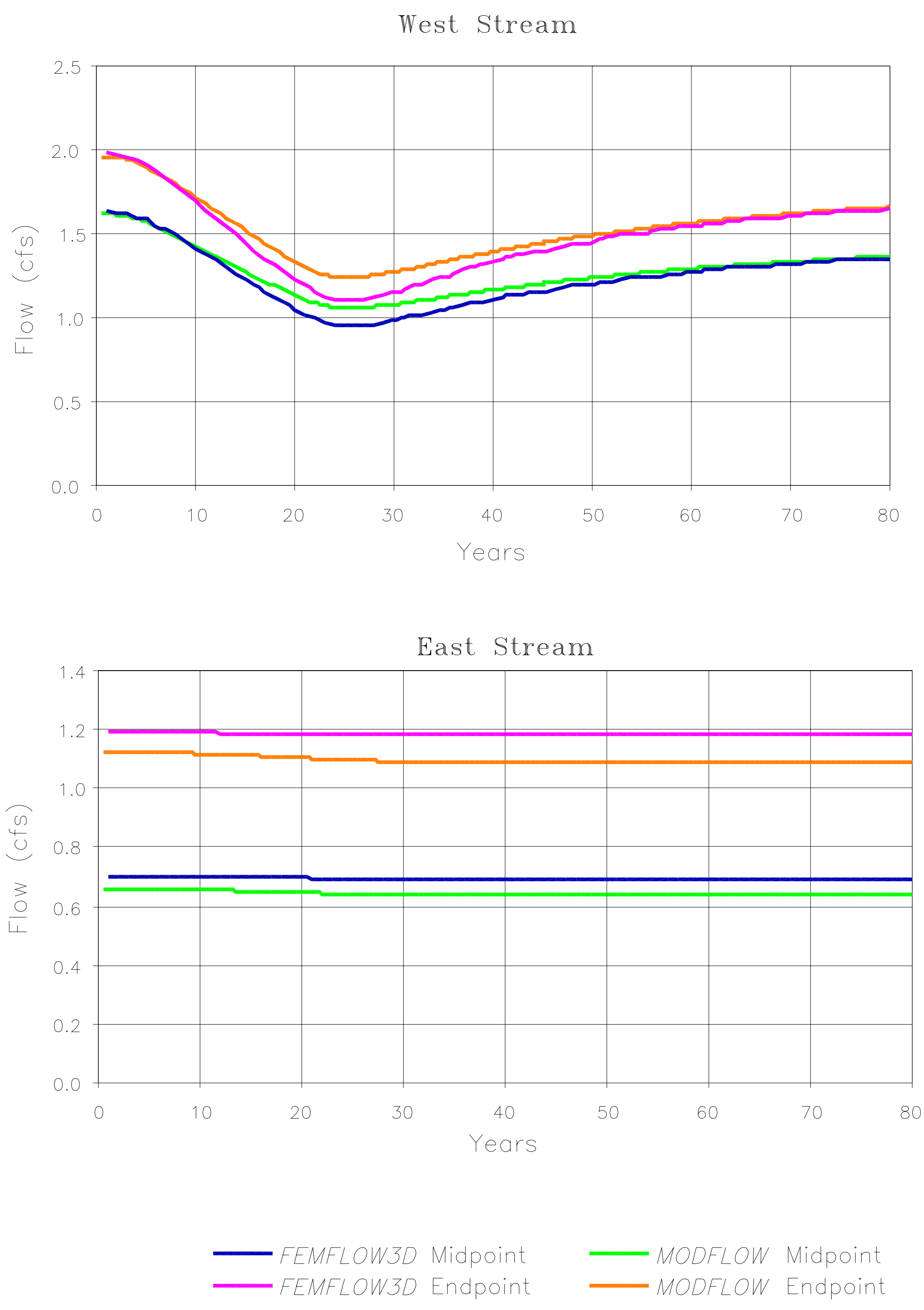


HCI HYDROLOGIC CONSULTANTS, INC. — HC|TASCA an company

JOB NO.	HCI–1827	DATE:	21 JUN 06
BY:	HL	DWG FILE:	FLUX–EAST–WESTa
DRAWN:	SAC	PLOT FILE:	FLUX–EAST–WESTa
CHECKED:		PLOT DATE:	26 JUN 06

Calculated Flux from Eastern Compartment to Western Compartment through Low Permeability Fault for Contrived Two–Compartment Problem

FIGURE 17

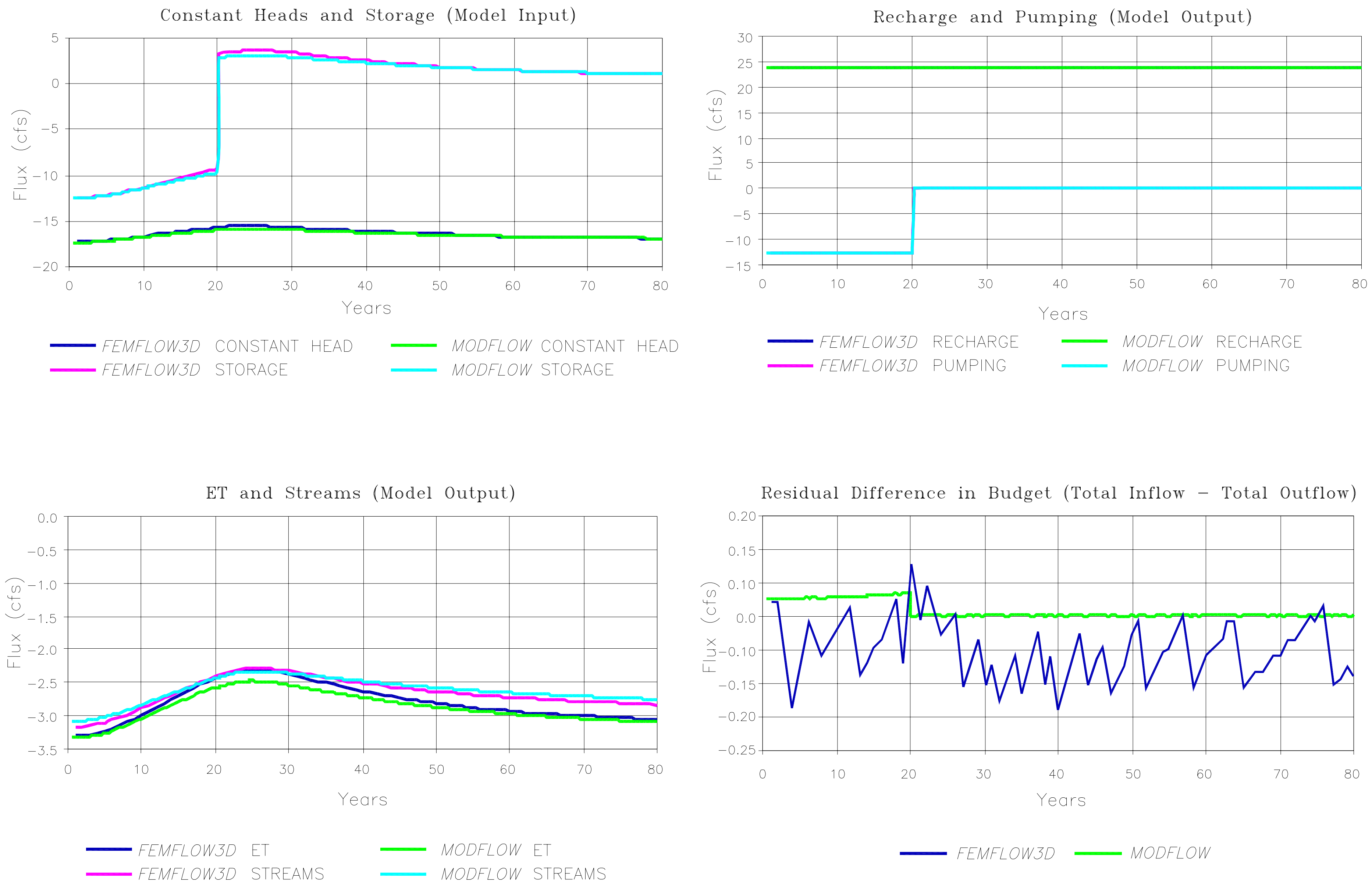


JOB NO.	HCI-1827	DATE:	21 JUN 06
BY:	HL	DWG FILE:	STREAM-FLOW-TM5a
DRAWN:	SAC	PLOT FILE:	STREAM-FLOW-TM5a
CHECKED:		PLOT DATE:	26 JUN 06

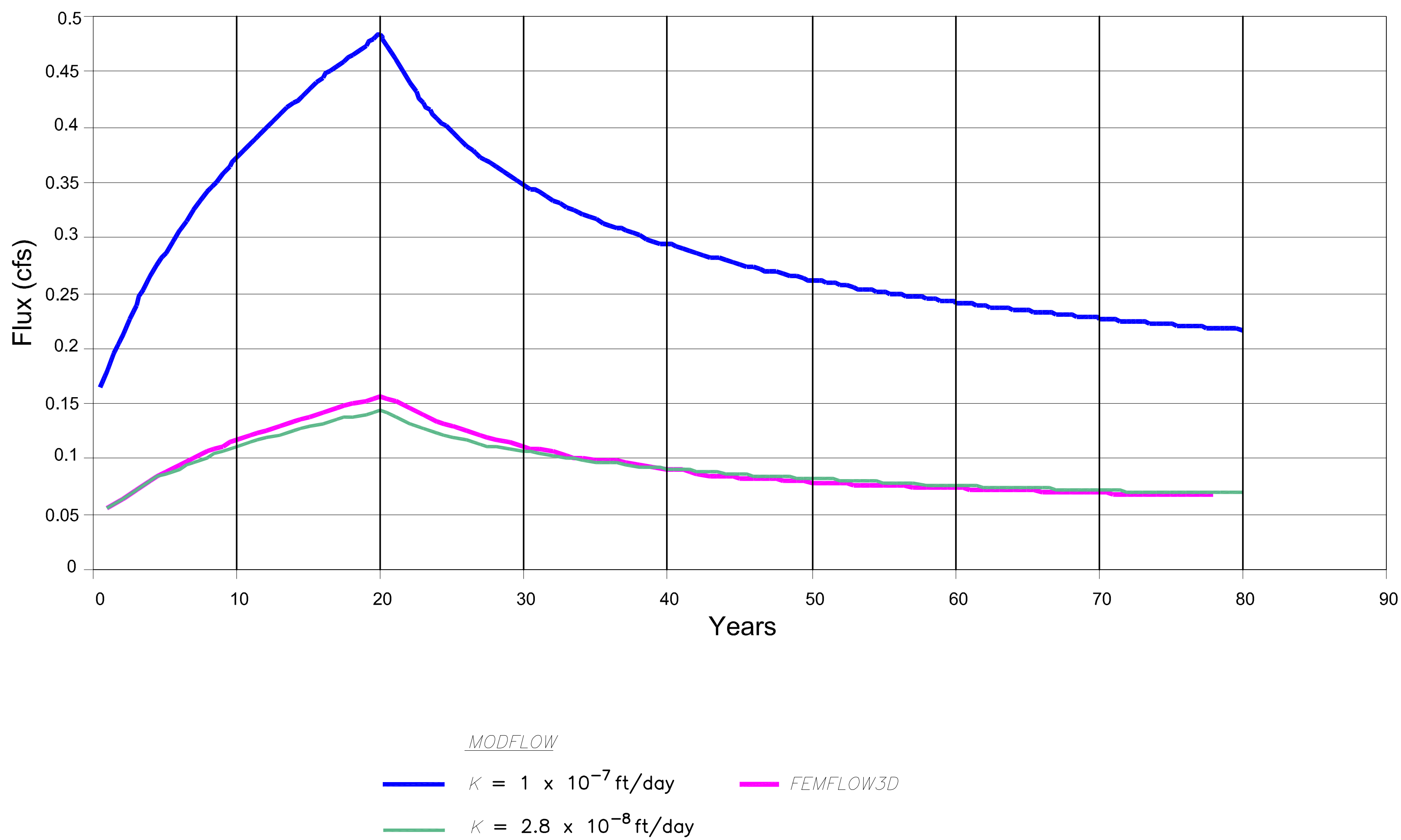
HCI HYDROLOGIC CONSULTANTS, INC. — an HC|TASCA company

Calculated Streamflows at Midpoints and Endpoints of Streams

FIGURE 18



HCI HYDROLOGIC CONSULTANTS, INC. — HC TASCA an company	JOB NO. HCI–1827	DATE: 26 JUN 06	Calculated Water Budgets	FIGURE 19
	BY: HL	DWG FILE: W–BUDGETS–TM5a		
	DRAWN: SAC	PLOT FILE: W–BUDGETS–TM5a		
	CHECKED:	PLOT DATE: 26 JUN 06		

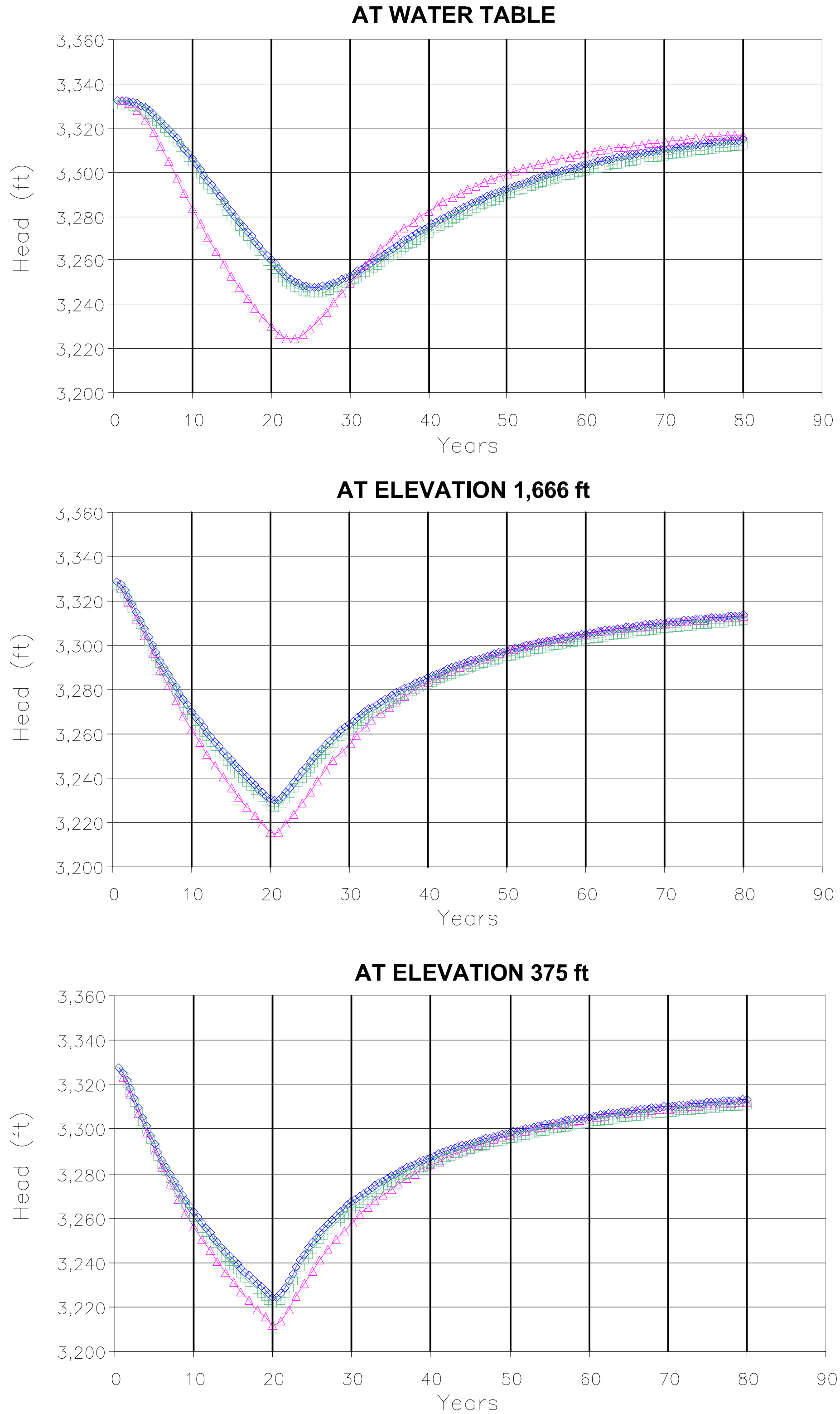


HCI HYDROLOGIC CONSULTANTS, INC.
HC TASCA an company

JOB NO.	HCI–1827	DATE:	26 JUN 06
BY:	HL	DWG FILE:	CALC–FLUX–TM5
DRAWN:	SAC	PLOT FILE:	CALC–FLUX–TM5
CHECKED:		PLOT DATE:	26 JUN 06

Calculated Flux from Eastern Compartment to Western Compartment through Low Permeability Fault Using Different *K* Values of *HFB*

FIGURE 20



MODFLOW

$K = 1 \times 10^{-7}$ ft/day

$K = 2.8 \times 10^{-8}$ ft/day

FEMFLOW3D

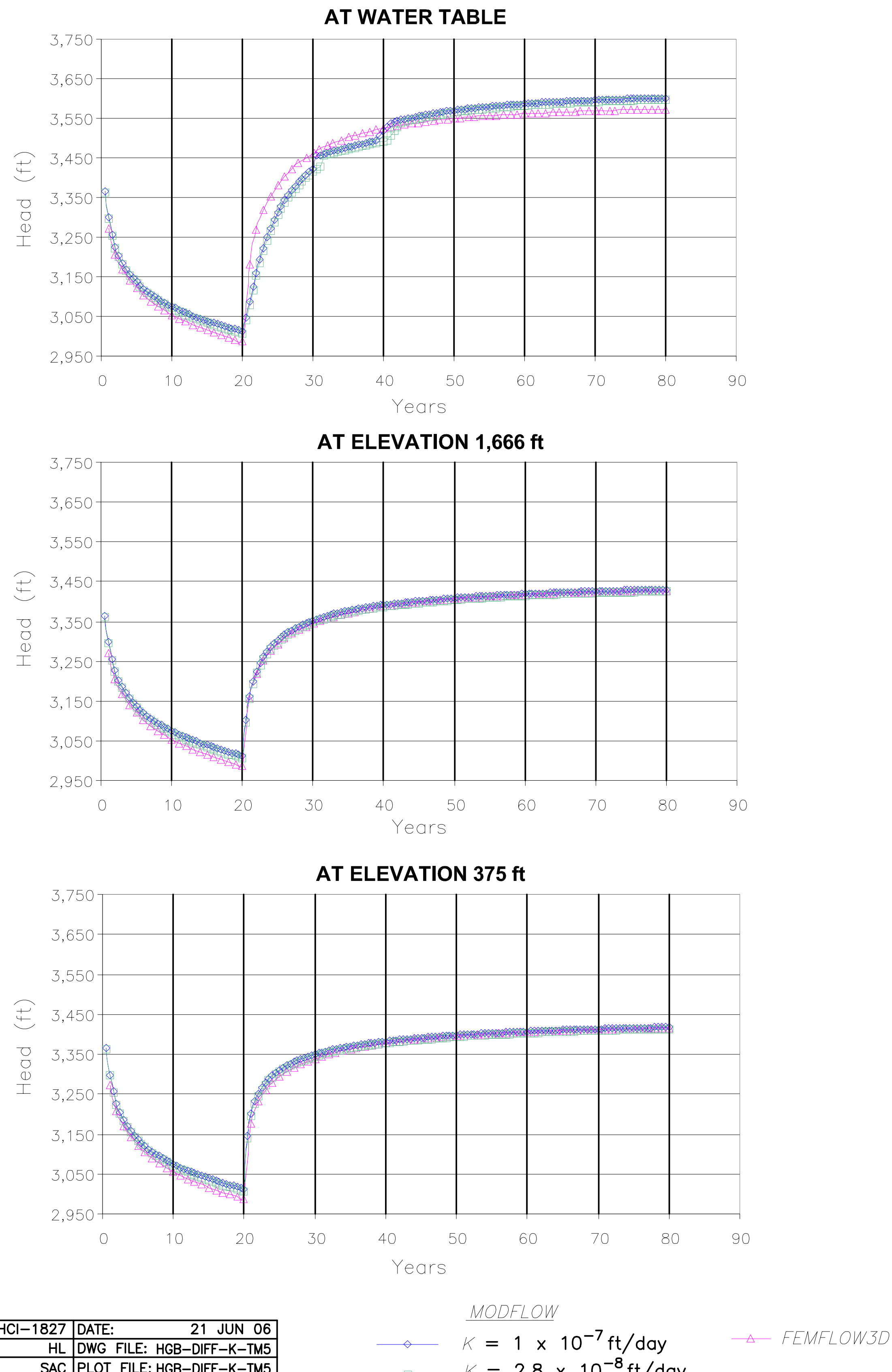
JOB NO.	HCI–1827	DATE:	21 JUN 06
BY:	HL	DWG FILE:	HGA–DIFF–K–TM5
DRAWN:	SAC	PLOT FILE:	HGA–DIFF–K–TM5
CHECKED:		PLOT DATE:	26 JUN 06

HCI HYDROLOGIC CONSULTANTS, INC.

HC ITASCA an company

Hydrographs of Calculated Hydraulic Heads at Point A at Three Different Elevations Using Different *K* Values of *HFB*

FIGURE 21

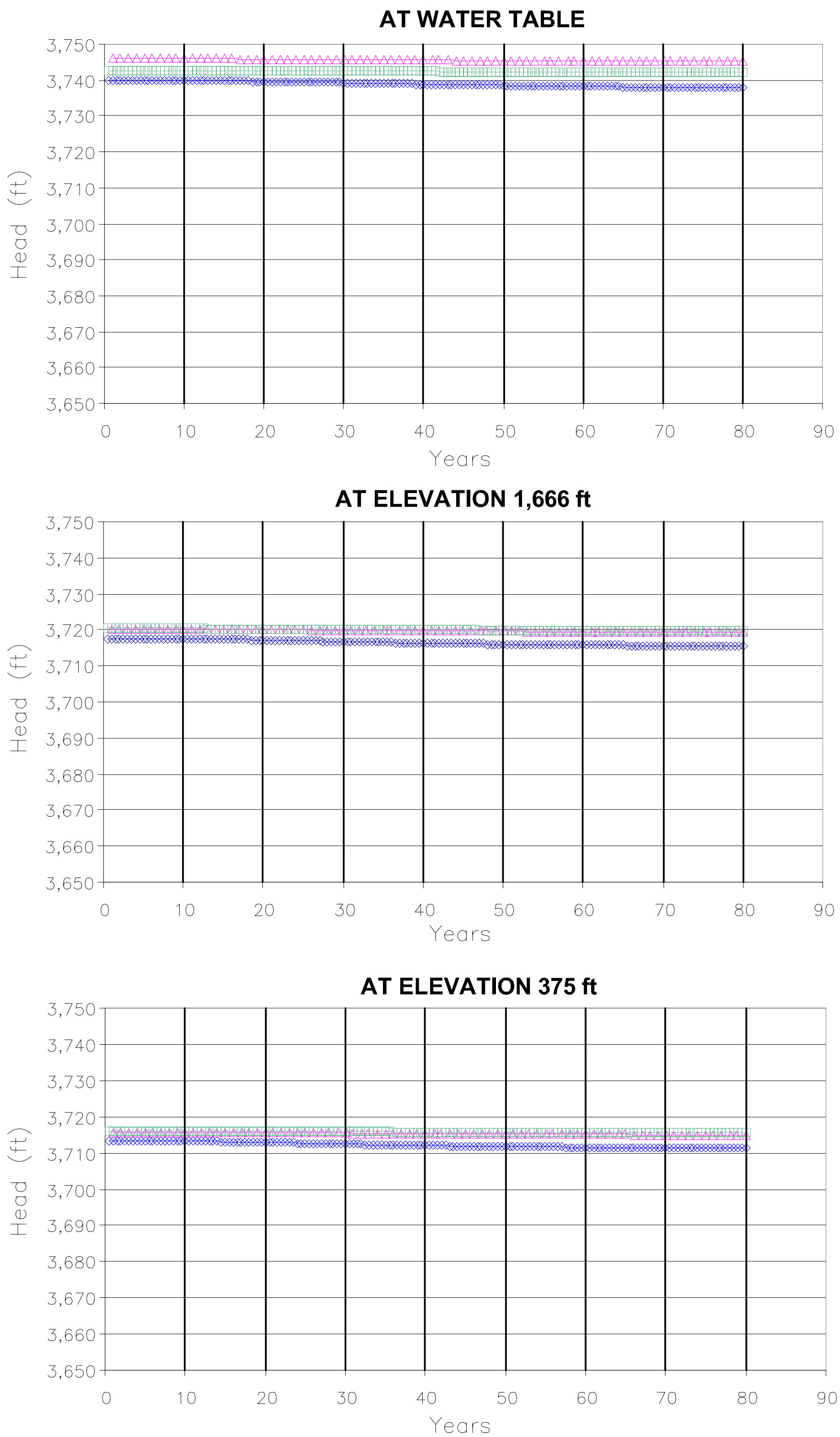


JOB NO. HCI–1827	DATE: 21 JUN 06
BY: HL	DWG FILE: HGB–DIFF–K–TM5
DRAWN: SAC	PLOT FILE: HGB–DIFF–K–TM5
CHECKED:	PLOT DATE: 26 JUN 06

HCI HYDROLOGIC CONSULTANTS, INC.
HC TASCA an company

Hydrographs of Calculated Hydraulic Heads at Point B (Pumping Well) at Three Different Elevations Using Different *K* Values of *HFB*

FIGURE 22



MODFLOW

$K = 1 \times 10^{-7}$ ft/day

$K = 2.8 \times 10^{-8}$ ft/day

FEMFLOW3D

JOB NO.	HCI–1827	DATE:	21 JUN 06
BY:	HL	DWG FILE:	HGC–DIFF–K–TM5
DRAWN:	SAC	PLOT FILE:	HGC–DIFF–K–TM5
CHECKED:		PLOT DATE:	26 JUN 06

HCI HYDROLOGIC CONSULTANTS, INC.

HC ITASCA an company

Hydrographs of Calculated Hydraulic Heads at Point C at Three Different Elevations Using Different *K* Values of *HFB*

FIGURE 23

TABLE 1

Hydraulic Properties of Hydrostratigraphic Units used in Contrived Problem

Parameter	Units	Upper Unit	Lower Unit
K_{xx}	ft/day	0.1	1
K_{yy}		0.1	1
K_{zz}		0.01	0.1
Specific Yield	dimensionless	0.01	0.01
Specific Storage	ft^{-1}	1×10^{-5}	1×10^{-5}

TABLE 2

Locations and Specified Elevations of Stream Nodes

FEMFLOW3D				*MODFLOW*			
Easting (ft)	**Northing (ft)**	**Length of Reach (ft)**	**Elevation of Streambed (ft, NGVD)**	**Easting (ft)**	**Northing (ft)**	**Length of Reach (ft)**	**Elevation of Streambed (ft, NGVD)**
Stream 1							
25,000	65,000	5,000	3,400.0	25,000	65,000	5,000	3,400.0
25,000	60,000	5,000	3,366.7	25,000	60,000	5,000	3,366.7
25,000	55,000	5,000	3,333.4	25,000	55,000	5,000	3,333.3
25,000	50,000	5,000	3,300.0	25,000	50,000	5,000	3,300.3
25,000	45,000	5,000	3,266.7	25,000	45,000	5,000	3,266.7
25,000	40,000	5,000	3,233.3	25,000	40,000	5,000	3,233.3
25,000	35,000	5,000	3,200.0	25,000	35,000	5,000	3,200.0
25,000	30,000	5,000	3,166.7	25,000	30,000	5,000	3,166.7
25,000	25,000	5,000	3,133.3	25,000	25,000	5,000	3,133.3
25,000	20,000	5,000	3,100.0	25,000	20,000	5,000	3,100.0
25,000	15,000	5,000	3,066.7	25,000	15,000	5,000	3,066.7
25,000	10,000	5,000	3,033.4	25,000	10,000	5,000	3,033.4
Stream 2							
65,000	65,000	5,000	3,600.0	65,000	65,000	5,000	3,600.0
65,000	60,000	5,000	3,566.7	65,000	60,000	5,000	3,566.7
65,000	55,000	5,000	3,533.4	65,000	55,000	5,000	3,533.3
65,000	50,000	5,000	3,500.0	65,000	50,000	5,000	3,500.0
65,000	45,000	5,000	3,466.7	65,000	45,000	5,000	3,466.7
65,000	40,000	5,000	3,433.3	65,000	40,000	5,000	3,433.3
65,000	35,000	5,000	3,400.0	65,000	35,000	5,000	3,400.0
65,000	30,000	5,000	3,366.7	65,000	30,000	5,000	3,366.7
65,000	25,000	5,000	3,333.3	65,000	25,000	5,000	3,333.3
65,000	20,000	5,000	3,300.0	65,000	20,000	5,000	3,300.0
65,000	15,000	5,000	3,266.7	65,000	15,000	5,000	3,266.7
65,000	10,000	5,000	3,233.3	65,000	10,000	5,000	3,233.3

TABLE 3

Calculated Water Budgets under Steady-State Conditions

Component (cfs)	Calculated by		
	FEMFLOW3D	***MODFLOW***	
		$K_{HFB} = 1x10^{-7}$ *ft/day*	$K_{HFB} = 2.8x10^{-8}$ *ft/day*
Recharge	23.73	23.78	23.78
Constant Head	-17.24	-17.35	-17.36
ET	-3.30	-3.35	-3.33
Streams	-3.15	-3.08	-3.10
Inflow - Outflow	0.04	0	-0.01
Flow from Eastern to Western Compartment	0.049	0.15	0.048