Open-File Report # NM/Baca-14

Environmental (Cont'd.)

No.	Transfer Date	Release Date	Title
7.	A	A	"The Biota of Redondo Creek Canyon, Sandoval County, New Mexico, with Emphasis on Big Game Species and Rare, Endangered or Threatened Species", by Southwest Environmental Research and Development Corporation, October 1974.
8.	A	A	"Report on Reconnaissance of Redondo Creek, Redondo Border, Sulfur Canyon, Alamo Canyon and Valle Seco Areas with Proposals and Budget Estimates for Biological Baseline Studies", Whitford Ecological Consultants, May 1975.
9.	B	B	"Winter Activity and Habitat Use by Elk in the Redondo Creek Area with Comments on Activities and Relative Abundance of Other Species", by Whitford Ecological Consultants, August 1975.
10.	B	B	"The Biota of the Baca Geothermal Site", by Whitford Ecological Consultants, November 1975.
11.	B	B	"Studies of Rare and/or Endangered Species on the Union-Baca Geothermal Lease and Surrounding Area with Discussion of Other Species", by Whitford Ecological Consultants, 1975(?).
12.	B	B	Hydrology of the Region Surrounding the Valles Caldera by Water Resources Associates - 1977.
13.	B	B	Appendices II and III to Hydrology of the Region Surrounding the Valles Caldera, Water Resources Associates - 1977.
14.	B	B	Model of Streamflow Depletion of the Jemez River by Geothermal Development in the Valles Caldera, New Mexico by Water Resources Associates, Inc. - 1977 - Addendum to Hydrology, Jemez Mountains, New Mexico - 1977.

DEL PYLE

SEP 1 9 1977

MODEL OF STREAMFLOW DEPLETION OF THE JEMEZ RIVER BY GEOTHERMAL DEVELOPMENT IN THE VALLES CALDERA, NEW MEXICO

ADDENDUM TO

HYDROLOGY
JEMEZ MOUNTAINS, NEW MEXICO

March 1977

WATER RESOURCES ASSOCIATES, INC.
Scottsdale, Arizona

MODEL OF STREAMFLOW DEPLETION OF THE JEMEZ RIVER BY GEOTHERMAL DEVELOPMENT IN VALLES CALDERA, NEW MEXICO

Introduction

This is a description of the model that was developed to estimate streamflow depletion which would result from geothermal development in the Valles Caldera, described in a report of March 30, 1977[1].

The flow in the Jemez River is partly from thermal springs located along the River's course. Chemical analysis of this spring water suggests that a small part of the flow comes from the interior of the Valles Caldera. The Caldera contains an underground reservoir of superheated water suitable for geothermal development. Proposed utilization of this thermal water would lower the hydrostatic pressure inside the Caldera, resulting in less outflow to the springs.

The purpose of this report is to (1) explain the model that was written to estimate the streamflow depletion, and (2) give the results obtained using this model.

The material is organized in such a manner that it is possible to follow the derivation of the model. The original model, developed in March 1977, is briefly discussed and details of a refinement of that model are presented. Derivation of the model is given as Appendix I, and computational results are presented as Appendix II.

Original Model

In March 1977, a simplified computer model was used to estimate the leakage out of the Valles Caldera. The model was written for an Olivetti P652 computer. This model and the results obtained from it are briefly outlined in the March 1977 report.

Subsequent evaluation revealed that this model probably was over simplified and certain modifications should be made. In addition, the Caldera dimensions used in the first model were larger than later determined from geologic maps. The earlier model also assumed that the head inside the Caldera was approximately that of the Jemez River where it crossed the Caldera's rim. Possible recharge from the Jemez River into the Caldera was ignored.

For these reasons, it was decided to refine the early model into a more flexible one, which is the subject of the following description.

Refined Model of the Valles Caldera

General Equations

Like the first model, the second was derived from a consideration of Darcy's law. (See Appendix I for a complete derivation of the model.) A generalized diagram of the flow out of the Caldera and into the Jemez River was sketched out (Figure 1, Appendix I) and then, each of the terms in Darcy's law was solved for in terms of variables in the diagram. The final equations are as follows:

1. $d = r\left(\frac{1+\cos\Theta}{\sin\Theta} - 1\right)$

2. $\Delta h_{(n-1)} = \frac{(R - Q_{(n-1)} - W)\Delta t}{\eta(r^2\Pi)}$

At time equals "t_n", the leakage "Q", flowing out of one quadrant of the Caldera and to one side of the River is given by:

3. $Q_n = \sum_{\Pi/2}^{\Theta_1} \frac{T(h_{(n-1)} + \Delta h_{(n-1)} - h_r + gd)(r\Delta\Theta + \frac{1}{4}[d_{\Theta} - d_{(\Theta-\Delta\Theta)} - r\Delta\Theta])}{[(\frac{(\Pi-\Theta)r}{\tan\Theta})^2 + (\beta - h_r + gd)^2]^{\frac{1}{2}}}$

Because two quadrants contribute leakage to the River, the leakage from each quadrant must be computed and added together to obtain the total leakage, Q_T at time "t_n":

4. $Q_T = Q_1 + Q_2$

Where

d = distance downstream from Caldera rim.

Θ = angle (in radians) measured from a line perpendicular to the stream, and passing through the center of the Caldera. (See Appendix I)

r = average radius of the Caldera.

$\Delta h_{(n-1)}$ = change in head inside the Caldera due to leakage out of the Caldera, withdrawal of water for steam and recharge into the Caldera.

R = recharge into the Caldera; this quantity is a constant rate, independent of the water pressure inside the Caldera.

$Q_{(n-1)}$ = rate of leakage out of the Caldera during the previous time increment.

W = rate of withdrawal of water for steam production; this quantity is independent of the water pressure inside the Caldera.

Δt = time increment over which Q_n is evaluated.

η = porosity of the aquifer producing the hot water.

Θ_i = initial angle (in radians) for quadrant 1.

T = transmissivity of the aquifer that conducts the water from the Caldera to the River.

h_n = hydrostatic or "free water" elevation inside the Caldera.

h_r = elevation of Jemez River as it crosses the rim of the Caldera.

g = gradient of River channel.

$\Delta\Theta$ = angle increment (in radians).

B = elevation of the bottom of the caprock.

Q_1 = rate of leakage into Jemez River contributed from quadrant 1 (southeast of the River).

Q_2 = rate of leakage into Jemez River contributed from quadrant 2; this quantity is computed in a manner similar to "Q". Quadrant 2 is northeast of the River.

Boundary Conditions

Analysis of the groundwater contours around the Valles Caldera indicated that the leakage into the Jemez River came from quadrant 1, specifically from between the angles of 33° and 90°. Quadrant 2 might have contributed some leakage from between 74° and 90°. Consequently, these values were converted to radians and used as boundary conditions.

Initial Conditions

The transmissivity of the aquifer was determined by first setting the rate of withdrawal for steam production "W" to zero (i.e. no pumpage from the Caldera) and then adjusting the transmissivity so that the leakage out of the Caldera equalled the recharge. Using this adjusted transmissivity, the program was then run using the desired value of "W". For purposes of calibration, an initial leakage of 165 gpm was used. This value was estimated as the contribution of Caldera water to the current spring flow using dilution ratios.

In calibration of the model, two critical assumptions were made. First, the total leakage from the Caldera is about 165 gpm. Second, the leakage from the Caldera (and recharge) has been constant with time, with no streamflow depletion until geothermal development begins. Historical records indicate that this may not be true. Renick[2] indicated that the hot spring activity along the Rio Salado has decreased with time.

Additional Considerations

Three factors strongly influence the results obtained using this program. They are (1) the porosity of the material inside the Caldera, (2) boundary conditions, and (3) the size of increments used in the analysis. Other factors probably influence the leakage but are not considered in this model. They include a strongly developed network of faults running south out of the Caldera, and the effects of superheated water on the hydrostatic head and on the transmissivity.

Porosity of the rock units controls the rate at which the head inside the Caldera is lowered as water is withdrawn. In this particular study, decreasing the porosity by a factor of 10 will increase the stream depletion by a similar magnitude.

It is believed that a porosity of about 10% is correct. With such a porosity, the streamflow depletion would not be more than four or five gallons per minute after fifty years of water use by a 55 MW plant. If a porosity of 1% is used, the depletion is about ten times this figure, or close to that projected using the first model.

The boundary conditions influence the size of the area through which water can flow out of the Caldera. The larger the area, the lower the transmissivity will have to be when calibrating the model. Because of this, the transmissivity partially compensates for changes made in estimating the boundary conditions. The boundary conditions are based on the analysis of shallow water table contours around the Valles Caldera.

Drainage out of the Caldera probably occurs as flow through deeper aquifers or possibly fault zones. Such flow may not influence the shallow water table in rock units above it, and consequently, boundaries that limit flow out of the Caldera are hard to place.

Two increments were used in the model. These were a time increment, "Δt", and an angle increment, "$\Delta \Theta$". An angle increment of one degree (converted internally in the program to radians) was used in the final series of calculations. Using an angle increment of 0.1 degree did not significantly improve the accuracy of the model. It did, however, take ten times as long to run.

A time increment of one year (converted internally in the program to days) caused a constant error of about a half a gallon per minute. After determining the magnitude of this error, an increment of one year was used and the results were corrected.

The effects of faulting south of the Caldera are unknown. Possibly, these faults tap small quantities of water directly from the Caldera. This water then flows southward until it reaches a location where it can leak into the Jemez River.

The temperature of the water influences two of the quantities used in this model. (Neither of these quantities has been adjusted to compensate for the effects of temperature.) Superheated water has a density of about 43 lbs/ft^3 at 590°F. This is only about 70% of the density of water at room temperature (62.32 lbs/ft^2 at 68°F). Consequently, a column of superheated water exerts less pressure, and has less effective head, than a column of cool water of the same height. As a result of this, one would expect less leakage out of the Caldera than is calculated using uncorrected equations. However, superheated water (600°F) has a viscosity of about 0.087 cp while cooler water (68°F) has a viscosity of about 1.0 cp. As a result of this lowered viscosity, the transmissivity of the aquifer would be higher, and more leakage than that calculated would occur. Consequently, the effects of decreased density are partially compensated for by the effects of increased transmissivity. It is believed that the initial calibration of the model decreases the magnitude of these apparent differences.

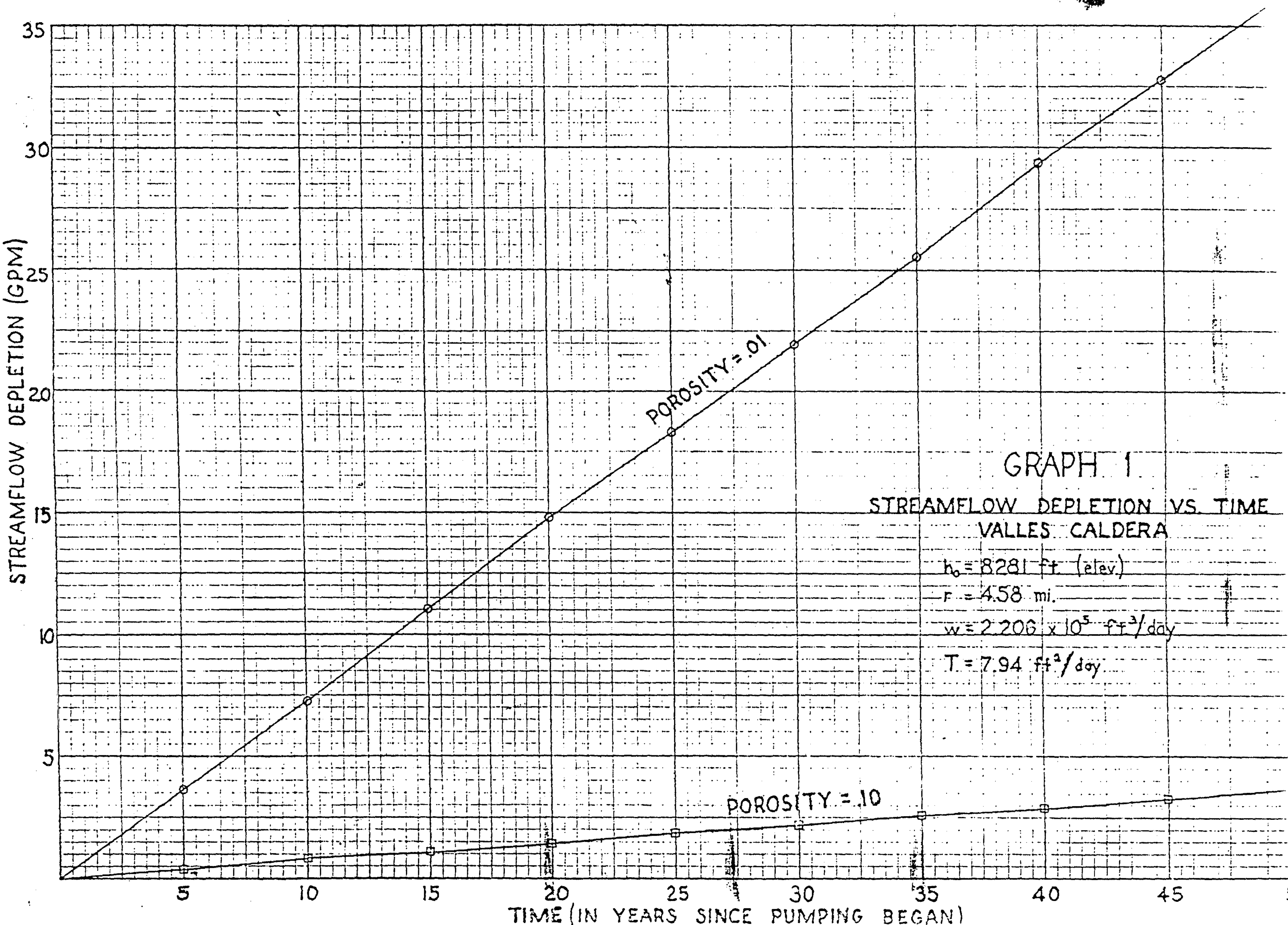
Results

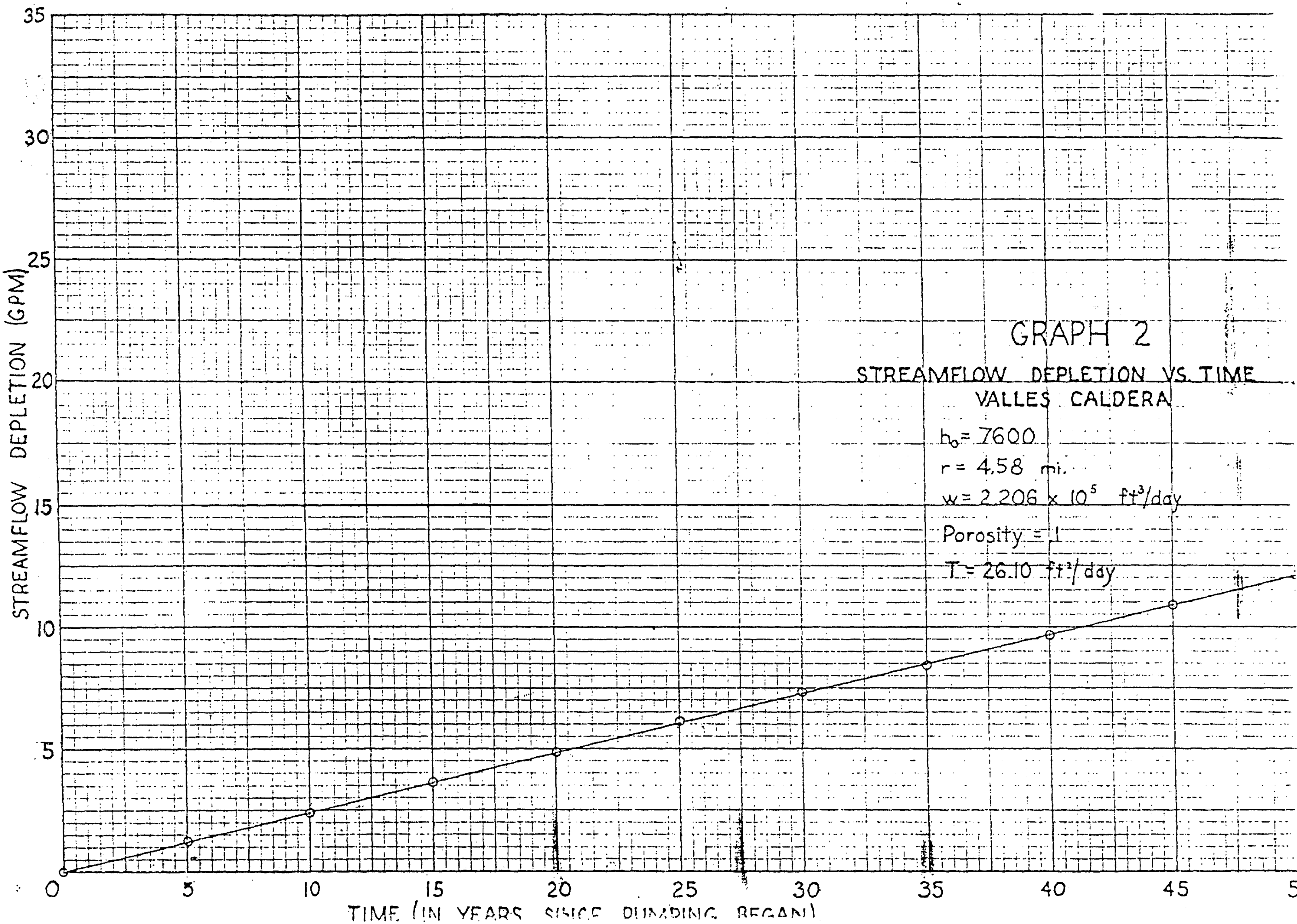
The following two graphs summarize the results of the model developed to estimate the streamflow depletion of the Jemez River. The first graph is based on a static head of 8281 feet inside the Caldera. The porosities used in the model were 0.10 and 0.01. It is believed that the depletion using a porosity of 0.01 is too high, although these results do agree with those obtained using the original model.

The last graph used a head of 7600 feet above sea level inside the Caldera, and a porosity of 0.10. It is believed that this graph is a better estimate of the streamflow depletion.

[1] Hydrology, Jemez Mountains, New Mexico, Water Resources Associates, Inc., March 1977

[2] U. S. Geological Survey Water Supply Paper 620


GRAPH 1
STREAMFLOW DEPLETION VS. TIME
VALLES CALDERA
h₀ = 8281 ft (elev)
r = 4.58 mi.
w = 2.206 x 10⁵ ft³/day
T = 7.94 ft²/day
POROSITY = .01
POROSITY = .10
STREAMFLOW DEPLETION (GPM)
TIME (IN YEARS SINCE PUMPING BEGAN)
35
30
25
20
15
10
5
5
10
15
20
25
30
35
40
45



GRAPH 2
STREAMFLOW DEPLETION VS. TIME
VALLES CALDERA
h_o = 7600
r = 4.58 mi.
w = 2.206 × 10^5 ft³/day
Porosity = .1
T = 26.10 ft²/day
STREAMFLOW DEPLETION (GPM)
35
30
25
20
15
10
5
0
5
10
15
20
25
30
35
40
45
TIME (IN YEARS SINCE PUMPING BEGAN)

APPENDIX I

DERIVATION OF MODEL

APPENDIX I

Derivation of Model

Darcy's Law:

1. $Q = K(\frac{dh}{dl})A = Kb(\frac{dh}{dl})(\alpha) = T(\frac{dh}{dl})(\alpha)$

where:

Q = leakage into Jemez River

K = hydraulic conductivity

$\frac{dh}{dl}$ = hydraulic gradient

A = discharging area

b = thickness of aquifer

α = arc length of Caldera's rim through which discharge occurs

T = transmissivity

Figure 1 illustrates generalized streamlines leaving the Caldera and entering the Jemez River. Such streamlines are circular with their centers located on the alignment of the River. Two adjacent streamlines make a flow tube. Using Darcy's law, the flow from the Caldera to the River through a given flow tube can be estimated:

2. $q = T(\frac{dh}{dl})(\alpha) \simeq T(\frac{h_n - \bar{h}_j}{\bar{L}})(r\Delta\Theta + c)$

where:

q = discharge through a flow tube.

h_n = hydrostatic head inside the Caldera (an elevation) during the current time increment (at time t_n).

h_j = average hydrostatic head at the discharging end of the flow tube; this is assumed to be the average elevation of the Jemez River channel between the two streamlines.

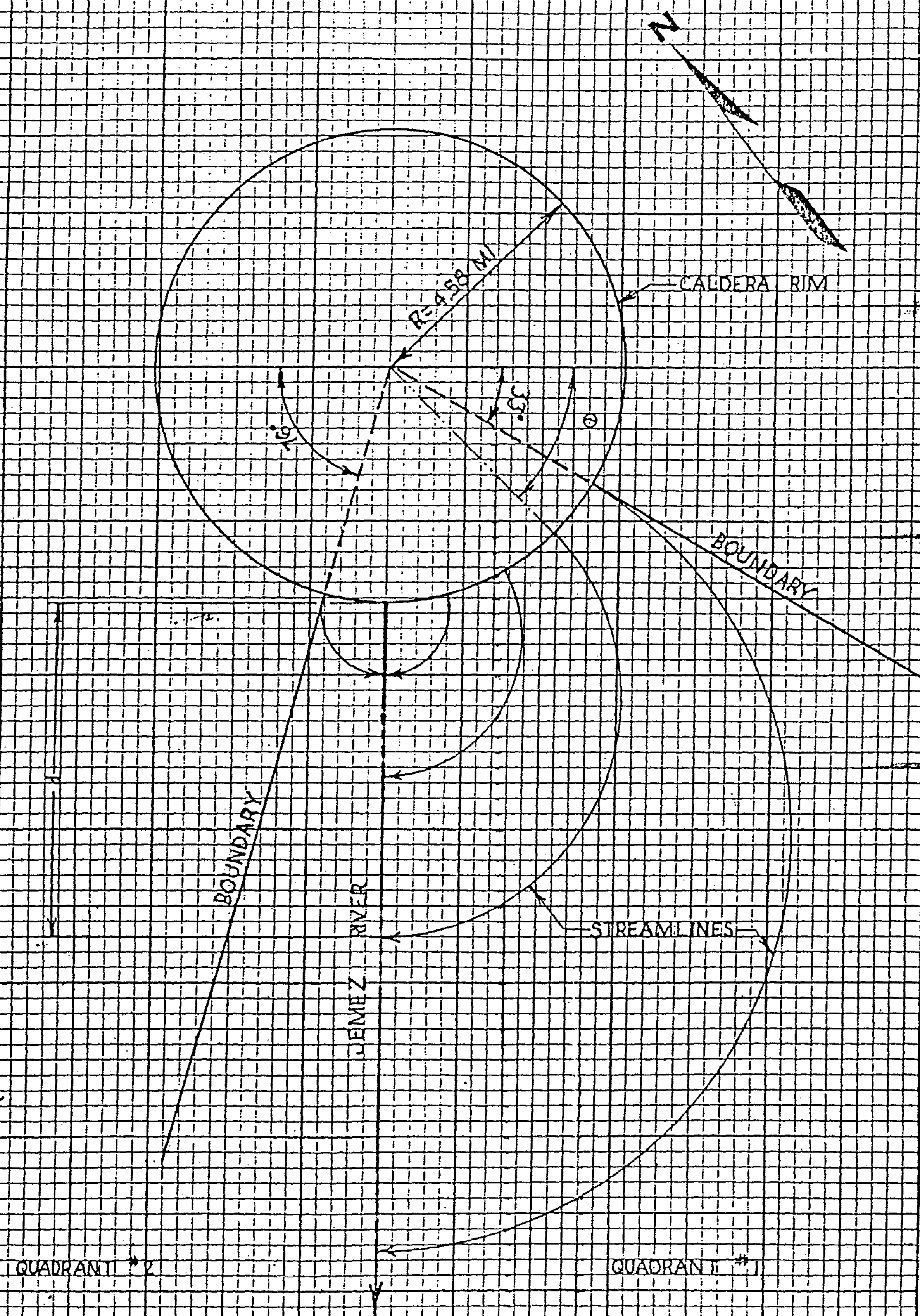
$\bar{L}$ = average length over which the head drop $(h_c - \bar{h}_j)$ occurs; i.e., the sum of the lengths of the two streamlines divided by two.

r = radius of the Caldera.

$\Delta\Theta$ = small incremental angle.

c = a correction factor.

FIGURE I: DIAGRAM OF THE MODEL OF THE VALLES CALDERA



A correction factor "c" is needed because the quantity $\frac{(h_c - \bar{h}_j)}{L}$ is the average hydraulic gradient, not the gradient at the Caldera's rim where the arc segment "rΔΘ" is measured. Because the flow tube expands, the hydraulic gradient is higher at the rim than it is elsewhere. The hydraulic gradient is lowest where the area of the flow tube is the widest, or near the River. The average gradient occurs somewhere between these points and has a unique discharging area associated with it. The correction factor increases the quantity "rΔΘ" so that it is the same as this unique area when multiplied by the aquifer thickness "b".

If the streamlines outlining the flow tube are close enough together, then the length of each is approximately the same. The average elevation where the streamlines intersect the River channel will also be similar. Consequently, equation #2 can be simplified as follows:

3. $q \approx T\left(\frac{h_n - h_j}{L}\right)(r\Delta\Theta + c)$ where $\Delta\Theta$ is very small

where:

h_j = elevation where the streamline(s) intersect the River channel.

L = length of the streamline(s).

To obtain the total leakage, the discharges through all the flow tubes are summed:

4. $Q = q = T\left(\frac{h_n - h_j}{L}\right)(r\Delta\Theta + c)$

The change in head is evaluated as follows:

5a. $h_n = h_{(n-1)} + \Delta h_{(n-1)}$

5b. $h_j = h_r - gd$

5c. $\Delta h_{(n-1)} = \frac{(R - Q_{(n-1)} - W)\Delta t}{\eta(\Pi r^2)}$

where:

h_n = hydrostatic head (an elevation) inside the Caldera during the current time increment (at time t_n).

$h_{(n-1)}$ = hydrostatic head inside the Caldera during the previous time increment (at time $t_{(n-1)}$).

$\Delta h_{(n-1)}$ = the change in the hydrostatic head inside the Caldera caused by recharge, leakage and pumpage.

h_r = elevation of the Jemez River as it crosses the rim of the Caldera.

g = gradient of the Jemez River channel.

d = distance downstream from the rim to the intersection of the River channel and streamline.

R = rate of recharge to the Caldera; this quantity is assumed to be constant.

$Q_{(n-1)}$ = rate of leakage out of the Caldera during the previous time increment.

W = rate of withdrawal of water out of the Caldera for steam production; this quantity is assumed to be constant.

Δt = time increment.

η = porosity of the aquifer inside the Caldera.

Πr^2 = area of the Caldera.

The length of each streamline is determined. A streamline has two components - h_r is the change in elevation and L_H is the horizontal distance. From geometrical considerations it can be shown L_H is equal to:

6a. $L_H = \frac{(\Pi - \Theta)r}{\text{Tan}\Theta}$

Θ = an angle (in radians) measured between a line passing through the center of the Caldera and perpendicular to the direction of streamflow, and a ray eminating from the center of the Caldera. A streamline begins where this ray intersects the Caldera's rim. Thus streamlines are a function of this angle.

The vertical change in elevation is as follows:

6b. $L_V = B-(h_r-gd) = (B-h_r+gd)$

where:

B = elevation at the base of the caprock

The length of the streamline is as follow:

$$6c. \quad L = [L_H^2 + L_V^2]^{\frac{1}{2}} = [(\frac{(\Pi-\Theta)r}{\tan\Theta}) + (B-h_r+gd)^2]^{\frac{1}{2}}$$

The distance from the rim downstream to the point where the streamline intersects the River channel is also solved for as a function of the angle Θ:

$$7. \quad d_\Theta = r(\frac{1+\cos\Theta}{\sin\Theta} - 1)$$

The correction factor "c" is then estimated. Analysis of the distribution of the hydraulic gradients indicated that the average gradient probably occurred fairly close to the Caldera rim. Consequently, the area was weighted so that it was nearer to the rim than to the River channel:

$$8. \quad c = \frac{1}{4}[d_{(\Theta)} - d_{(\Theta-\Delta\Theta)}) - r\Delta\Theta]$$

The correction factor calculates 0.25 of the difference between the discharging area of the rim and the discharging area in the River channel. This difference is then added to the discharging area of the Caldera. As mentioned in the text, it is felt that the initial calibration procedure of adjusting the transmissivity will compensate for errors estimating the discharging area.

The final step is to make the required substitutions into Equation #4 so that the final expression used in the model is obtained: (Note: Θ is in radians)

$$9. \quad Q_n = \sum_{\Pi/2}^{\Theta_i} \left[\frac{T(h_{(n-1)} + \Delta h_{(n-1)} - h_r + gd)(r\Delta\Theta + \frac{1}{4}[d_\Theta - d_{(\Theta-\Delta\Theta)} - r\Delta\Theta])}{[(\frac{(\Pi-\Theta)r}{\tan\Theta})^2 + (B-h_r+gd)^2]^{\frac{1}{2}}} \right]$$

where:

$$d = r(\frac{1+\cos\Theta}{\sin\Theta} - 1)$$

$$\Delta h_{(n-1)} = \frac{(R-Q_{(n-1)}-W)\Delta t}{\eta(\Pi r^2)}$$

The computer model uses Equation #9 to compute the leakage "Q_n" at time "t_n". The leakage into the Jemez River from each of the two contributing quadrants is computed and added together to get the total leakage at time "t_n". Using this leakage, the change in head "Δh_n" computed and the static head inside the Caldera is then adjusted. Using this adjusted static head, a new leakage for time "$t_{(n+1)}$" is computed.

Two quadrants are necessary because Equation #9 does not hold when Θ is $\Pi/2$ radians (90°). The model computer leakage by starting at the $\Pi/2$ radians, substrating $\Delta\Theta$, and using this new angle to generate the first streamline. This process is repeated down to the boundary angle. The leakage for each flow tube in the quadrant are summed as the program progresses. In a similar manner, leakage from quadrant #2 is also computed. The calculations for quadrant #2 are the same since the model is symmetrical about the Jemez River. Boundary angles are different for the two quadrants. Quadrant #1 ran from $\Pi/2$ to ≈ 0.58 radians (33°). Quadrant #2 went from $\Pi/2$ to ≈ 1.33 radians (76°).

APPENDIX II

INITIAL INPUT INTO THE MODEL

APPENDIX II

Initial Input Into The Model

Radius of the Caldera (r)

The model assumed that the Caldera was circular, with a radius of 4.58 miles. In reality the Caldera is roughly elliptical, with a major axis diameter of 10.5 miles and a minor axis of 8 miles. The assumed average radius was derived as follows:

$$\text{Area of Caldera} = [(10.5 \times 8) \div 4] \times \Pi = 66 \text{ sq. miles}$$

A circle with the same area would have a radius of:

$$r = (66 \text{ sq. miles} \div \Pi)^{1/2} = 4.58 \text{ miles}$$

Elevation of the Base of the Caprock (B)

The elevations of the base of the Caprock were taken off of graphs of Temperature vs Elevation in the various Baca test wells. These elevations were then averaged. For purposes of this model an average elevation of 6435 feet was used.

Elevation of the Initial Hydrostatic Head in the Caldera (h_o)

In two of the runs using the model, the elevations of the free water surfaces in the Baca test wells were averaged to obtain a value used as the initial hydrostatic head inside the Caldera. This value was 8281 feet above sea level. The last run was based on an elevation of 7600 feet. This last run used a reduced elevation to simulate the effect of the reduced density of hot water.

Porosity (n)

Information provided by Union Oil suggested the permeability of the aquifer in the Caldera was 0.04 to 0.10. In the first and third runs, a porosity of 0.10 was used to estimate the effects of the porosity on the leakage. It is felt that a porosity of 0.10 is a better estimate.

Recharge (R)

Recharge to Caldera was estimated as 3.176×10^4 ft^3/day or about 266 ac/ft/yr. This is 165 gpm which was estimated as the initial leakage from the Caldera into the Jemez River.

Rate of Withdrawal For Power Production

A 55 MW power plant was assumed to consume 2.206×10^5 ft^3/day or about 1150 gpm.

The Gradient of the Jemez River

The gradient of the Jemez River below the Caldera's rim was plotted out; the gradient was calculated as being 0.0639 ft/ft for the first 18,000 feet downstream and 0.0136 ft/ft thereafter.

The Elevation of the Stream As It Crosses The Caldera Rim

An elevation of 7600 feet was used. This is roughly the elevation of La Cueva Campground.