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GEOLOGIC RESOURCES REPORT

(For Administrative Use Only)

2880 Geologic Resources and Services
Apache – Sitgreaves National Forests
Black River Exchange

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CATEGORY: Supplemental Ground Water Assessment

BRIEF OF SUMMARY AND CONCLUSIONS: The effect of multiple well pumping at hypothetically proposed development which could result from the Black River Land Exchange was evaluated using an analytical model and a numerical ground water flow model. The effects of pumping from 258 wells were evaluated for a hypothetical period of ten years, both with and without the effects of ground water recharge and using a range of hydraulic parameters. In general, different parameters can result in drawdown at the pumping center of about 3 to 17 feet, depending on parameters used. However, drawdown at a distance of one mile is much less sensitive and the variations are only on the order of one to three feet over the ten year period. Although ground water would initially be withdrawn more rapidly than can be recharged, the effect on the water table would be minimal. There is likely to be much less drawdown if the 258 potential residents are present for only part of the year.

FS TECHNICAL APPROVAL: 12-20-07

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I. Introduction

As a result of District Court Order Number CV 06-0368-PHX-MHM for the Black River land exchange, it became necessary to evaluate the potential results of pumping of the shallow volcanic and White Mountains aquifers[1] which would result from the hypothetical land development planned in the wake of the Black River land exchange. The order indicated that the Forest Service reported that the effect of pumping from multiple wells was "highly uncertain," and that this was not deemed acceptable by the court. This report is an effort to clarify the possibilities resulting from such multiple well pumping using some simple computer models. All analytical analyses were performed using the AquiferWin32 aquifer test analysis software, version 3.11. This software allows the development of an analytical model[2] using any number of pumping and monitoring wells with differing solutions depending on the nature of aquifer confinement[3] or non-confinement[4]. A MODFLOW finite-element model[5] was also constructed to evaluate the effect of added recharge on the cone of depression[6]. The pre- and post-processing for MODFLOW was done using the Visual MODFLOW software from Waterloo Hydrogeologic, version 4.2.

Pumping from the deeper C aquifer (Arizona Department of Water Resources, 2006; Bills and others, 2000; Hart and others, 2002) would most likely be accomplished from one or two community wells, as the cost of drilling a well to 1800 foot depth would be prohibitive for most land owners. A single analytical flow model was constructed for two pumping wells for comparative purposes.

Pumping from multiple wells; one per lot or 258 in all (worst case scenario), was simulated from the shallow water table[7] aquifer. The pumping volume was assumed to amount to 0.5 acre feet per year (afy), or 0.31 gallons per minute (gpm) for each lot. About 0.5 afy is typical household consumption for a family living year-round in a house. Consumption in this case is likely to be considerably less as most residents will only live in the area for part of a year. In total this rate would amount to 129 afy, or 80 gpm if all 258 wells were in use. Local wells in this aquifer are typically 100 to 300 feet deep, sometimes less.

II. Aquifer parameters

A. The C aquifer

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[1] Aquifer - A water-bearing layer of rock that will yield water in a usable quantity to a well or spring.
[2] Analytical model – A mathematical prediction of possibilities based on equations, rather than numerical approximations.
[3] A confined aquifer is under pressure by virtue of having an impermeable or semi-impermeable capping layer, such as shale. Water will rise in a well above the top of the aquifer in this case.
[4] An unconfined aquifer is not under pressure; water in a well rises to the level of the water in the aquifer, not above.
[5] A finite element model is a numerical approximation of the ground water flow equation. This is necessary when the amount of complexity is too great to solve analytically.
[6] Cone of depression – The decrease in the level of the water table that results from pumping at a well.
[7] Water table - The level in the saturated zone at which the pressure is equal to the atmospheric pressure, i.e. the level to which water rises naturally in a well.

The C aquifer is a multiple aquifer system, mainly composed of the Coconino Sandstone, but also contains portions of other geologic formations, including the Kaibab and Upper Supai Formations (Hart and others, 2002). In New Mexico, the equivalent of the Coconino Sandstone is the Glorieta Sandstone, De Chelly Sandstone, and the De Chelly Sandstone Member of the Cutler Formation. There have been no reliable local tests for determination of aquifer parameters performed for the C aquifer. However, according to Leake and others (2005) and S.S. Papadopulos & Associates (2005) the thickness of the C aquifer in the study area is on the order of 300 feet, the storage coefficient/specific yield is approximately 0.05 (meaning the aquifer is 0.05% void space which can be water-filled), and it is mainly unconfined with a transmissivity[8] on the order of 1500 ft^2/d. A single well has been drilled in the C aquifer, which was encountered at a depth of approximately 2300 feet. The drill log is given in Schwab (2005), Appendix C and may be only partially penetrating with respect to the C aquifer. Otherwise, it is consistent with the 300 foot thickness estimate. A pumping test was performed, but the water level was apparently only reported for the pumping well and the information is not useful for determination of aquifer characteristics.

B. Volcanic and White Mountains aquifer

The local shallow aquifers generally tapped by individual water users are the White Mountains aquifer and the shallow volcanic aquifer. They are hydrologically connected and continuous in the area. The saturated thickness is on the order of 200 to 300 feet. If the hypothetical Black River land exchange development ends up leaving each landowner to obtain their water supply independently, then there could end up being up to 258 relatively shallow wells in the local volcanic and White Mountains aquifers. There are no hard data sources for this aquifer regarding transmissivities and storage coefficients, therefore estimates had to be made. Schwab (2005) indicated that "*b*ased on existing information, properly drilled wells . . . in shallow . . . aquifers would be expected to yield an average of 9 gpm." If this can be assumed to be a specific capacity, then according to the method of Theis and others (1963) a transmissivity may be estimated. However, specific capacity is specified as gpm *per foot of drawdown*. Unfortunately, this latter part was not specified; so such an estimate should be considered a maximum value. A range of transmissivities from 100 to 1500 ft^2/d were evaluated. The correct value is probably intermediate to these numbers. A value of 500 ft^2/d considered to be very likely, as this would represent a hydraulic conductivity[9] of about 2 to 3 ft/d; very typical for sandstone and fractured igneous rock aquifers (Freeze and Cherry, 1979).

The storage parameter also had to be estimated for the White Mountains aquifer. An estimated value of 0.05 (The storage coefficient is a unitless number indicative of the fraction of the rock open for water saturation; equivalent to specific yield in unconfined aquifers) was utilized for the C aquifer model of Papadopulos & Associates (2005) in the Greer area and a value of 0.06 was used for specific yield in Leake and others (2005). Bills (2000) reports an average value of specific yield of 0.077 in the Flagstaff, AZ area. The 0.05 figure was used for the simulations of

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[8] Transmissivity - The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the aquifer thickness.
[9] Hydraulic conductivity: The capacity of a rock to transmit water. It is expressed as the volume of water that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow; i.e. a velocity.

this report, considering that it is the most conservative. Values of 0.1 to 0.2 are not unusual for unconfined aquifers and such a higher value indicates greater storage in the aquifer and consequently less drawdown for any given amount of pumping.

An assumption used is that of porous media flow, which is fundamental to the analytical solutions and to MODFLOW. There may be a considerable fracture flow component, but without knowing more about the fracture network in the area, application of this kind of modeling would require unacceptable assumptions due to the lack of knowledge. This lack of knowledge is an issue with fracture flow models even when there is considerable knowledge of their occurrence and orientation. Generally, however, the spacing of such fractures in these volcanic rocks is small enough to function as porous media flow on the scale of these simulations.

III. Pumping simulations

Schwab (2005) utilized 200 gpm as the probable draw on the aquifer. As indicated above, unless there is another major water user, 80 gpm is the likely maximum. However, if the pumping rate is greater; 160 gpm for example, the drawdown would be exactly twice as great at any given location. For this study, 80 gpm was used as the pumping rate; in 258 wells (one per lot at 0.31 gpm each) and in two (one per tract, one at 16.5 gpm and the other at 63.5 gpm). The MODFLOW simulation was only done for the 258 well scenario, since its purpose was only to evaluate the effect of adding recharge.

No heterogeneities in the aquifers were modeled because of the lack of such information. Therefore, for each scenario they are homogeneous, isotropic, and of infinite extent. In other words, the aquifer characteristics are the same in all directions. The values used for aquifer parameters consequently represent an averaged value of natural heterogeneity, adequate for problems of this scale. The MODFLOW simulation has boundaries several miles from the pumping center in order for it to behave as an infinite aquifer, since barriers to flow have not been reported and are uncertain. The analytical solutions already have an infinite aquifer built into their assumptions. The greatest effect a single, impermeable barrier of infinite extent may have, assuming it is very close to the pumping center would be to double any previously predicted drawdown. If barriers are present, the resulting drawdown effects would range somewhere in between the two results.

A. Analytical simulations

Analytical[10] evaluations were performed using the AquiferWin32 software package by Environmental Simulations, Inc. This package is a tool for evaluating aquifer tests by a number of methods. Only the Theis (1935) solution for confined conditions and the Neuman (1972) solution for water table aquifers were utilized. The flow modeling option was used which allows the input of any number of multiple wells. The Theis solution was used with a large storage coefficient to simulate a water table aquifer.

B. Finite element simulation

[10] An analytical solution is an exact solution to a series of equations, as opposed to numerical approximations used in most ground water models such as MODFLOW.

Because the Theis and Neuman analytical solutions do not take recharge into account, the drawdown curves they generate only represent drainage of the aquifer and are the maximum possible for any given aquifer parameters. For this reason a simple MODFLOW simulation was developed for the multiple well pumping scenario using the same parameters as the analytical solution. The boundaries were extended far enough horizontally to insure the cone of depression would not impinge upon them within the ten year time frame utilized. The entire model domain is 24.6 miles square. Pumping without recharge yielded the same solution as the analytical Theis solution, although the unconfined or water table parameters were used in MODFLOW. The Neuman solution generally yielded a drawdown 20 to 30% less, depending on parameters used. This is due to the Neuman solution taking into account gravity drainage of the aquifer, while the Theis solution assumes the aquifer will remain saturated, losing only artesian pressure, or head.

1. Model setup

A contour map of the project area with tracts A and B superimposed is shown in Figure 1. This template was used as a backdrop for locating the pumping wells; one per lot. The local geology is described in Schwab (2005). Pumping from multiple wells (one per lot) would most likely be accomplished using the White Mountains aquifer, as it is the most accessible and productive, and the C aquifer below would be too deep and expensive for individual household wells.

IV. Results

The cone of depression for the two well, analytical scenario is shown in Figure 2, and shows the results of pumping 80 gpm steadily for ten years from two wells. For this simulation, a transmissivity of 500 ft^2/d was used. The storage coefficient used was 0.05 for all simulations. The contour lines represent total drawdown in feet. Figure 3 shows the same situation, only the 80 gpm is distributed among all 258 potential household wells (0.31 gpm each). The red lines in each figure, labeled A-A' and B-B' in Figure 2, are the locations of two cross sections constructed for comparison of the two cones of depression. In Figures 4 and 5 the north-south and east-west 10 year drawdown cones are shown. The only difference in the two pumping schemes is that when pumping is only from two wells, the absolute drawdown at each well will be considerably greater than drawdown from many wells pumping at the same rate. However, only a short distance from the center of pumping the two results are essentially identical, simply because the same amount of water is being removed from the same general area. The Theis solution was used for both scenarios.

Figure 6 shows the 10 year contour map of the cone of depression using the Theis solution at a transmissivity of 100 ft^2/d, and Figure 7 shows the 10 year contour map of the Theis solution at a transmissivity of 1500 ft^2/d. The latter is a reasonable maximum possible value for the water table aquifer, as it is unlikely to have a greater transmissivity than the thicker C aquifer below. The 100 ft^2/d scenario is a reasonable minimal value. If the value were lower, it would not be a viable aquifer. The two situations show a maximum spread in the extent of the ten year cone of depression which might be expected.

This is compared to the Neuman solution for unconfined aquifers shown in Figure 8. The Theis solution shows somewhat greater drawdown because it does not take vertical gravity drainage of the aquifer into consideration, and is generally considered to be a more accurate analysis for water table aquifers. Figures 9 and 10 show the north-south and east-west cross sections, respectively for the 10-year Neuman water table, 258-well pumping scenario. Curves are shown at pumping rates of 100, 200, 500, and 1500 gpm, for comparison.

As discussed earlier, 80 gpm is a probable maximum rate of withdrawal since it assumes a full time resident occupation on each lot. If all residents were to spend only three months out of the year on their lot, an average rate of 20 gpm would be more likely. This cone of depression is also shown. These comparisons were made using the 258-well pumping scenario.

This last comparison was made without recharge of groundwater. For this, a numerical solution was used, because recharge is not accounted for in the analytical solutions of AquiferWin32. Three models were constructed for a transmissivity of 500 ft^2/d and storage coefficient of 0.05; a no recharge scenario, 0.1 inches and 0.2 inches of recharge. Recharge was applied in blanket fashion over the entire model domain. An evapotranspiration rate equal to the recharge rate was applied over the same area to insure that the undisturbed water table would not migrate artificially upward. The single model layer was designated “unconfined” by setting the appropriate factor in MODFLOW. The “no recharge” run results were virtually identical to the analytical Theis scenario (Figure 12). As is apparent in Figure 12, the addition of recharge decreased the magnitude of drawdown to a large degree. With 0.2 inches of recharge, drawdown is roughly half of what it is without recharge. This drawdown represents the water that is mined from storage. The model by Papadopulos & Associates (2005) of the Little Colorado basin used a value of 0.1 inches per year in the project area. However, the Papadopulos model was developed for evaluation of the deeper C aquifer only, and recharge for the shallower volcanic and White Mountains aquifers could be somewhat more. The Neuman solution is also plotted on Figure 12 for comparison. No recharge application was possible with this technique. The analytical Theis solution is shown on Figure 12 for comparative purposes; it is nearly identical to the MODFLOW no recharge results.

V. Conclusions

It is not possible to know what the exact hydrologic parameters are for the project area, since no local aquifer testing has been done. However, examining the values obtained for the better known C aquifer, some useful analyses and assumptions could be made. Whatever parameters were used, there was no appreciable difference in effect from using either two wells or 258 wells for a given cumulative withdrawal rate; with the exception of the deeper cone of depression in the immediate vicinity of the wells in the two-well version. For median values of 500 ft^2/d for transmissivity and 0.05 for a storage coefficient, expected lowering of the water table after ten years of pumping would be about 1.5 to 2.5 feet one mile from the center of pumping. At a distance of one mile from the pumping center, all values of transmissivity give similar results for the no-recharge scenarios. However, 10 year drawdown at the pumping center for the multi-well pumping simulations can vary from 3 to 17 feet, depending on the aquifer characteristics used. Addition of recharge in the form of blanket precipitation can reduce the amount of drawdown by one fourth to one half. Reducing withdrawals due to lower usage by part-year residents would also serve to reduce the amount of drawdown. A combination of recharge and lower water use could reduce drawdown one mile from the pumping center to about half a foot after ten years. However, whichever scenario is used, the water table is still declining at ten years and will continue to decline, albeit at a lesser rate every year.

All of the solutions assume that the aquifer is unconfined and 200 feet thick. A thicker aquifer would result in correspondingly less drawdown; i.e., 4 feet of drawdown would become 2 feet. All assume that all 258 wells would pump at the average rate of 0.50 acre feet per year (0.31 gallons per minute), which also assumes that all 258 residents would be on the site 365 days per year. The Theis solution, which is generally used for confined aquifers, is considered adequate for unconfined aquifers provided drawdown is a small percentage of saturated thickness. However, the Neuman solution for water table aquifers is generally considered to be a more accurate solution for this condition.

The table below shows the expected range of drawdown in feet for the indicated area, and the potential effect on existing wells. The effect means that if a well penetrates the water table initially by 100 feet, then drawdown of 17 feet would reduce the penetration to 83 feet, and the effect on that well would probably be unnoticed. If a well penetrates the water table by 30 feet, Then 17 feet of drawdown would reduce that penetration to 13 feet, which may have a detrimental effect on the user, depending on their water needs. If all residents of the new development were present for only one fourth of the year, the drawdown would be about one fourth of the values given below. The median value for hydraulic conductivity of 2.5 ft^2/d is the most likely for the known aquifer characteristics.

Parameters				Range of maximum drawdown*		
				Section 26 North half	Section 26 South half	Section 35 North half
Solution	T (ft^2/d)	S	S_y	22 wells	49 wells	9 wells
Theis	500	0.05		4 to 8 feet	3 to 5 feet	2 to 3 feet
Neuman	100		0.05	6 to 23 feet	3 to 12 feet	3 to 6 feet
Neuman	1500		0.05	2 to 3.5 feet	1.6 to 2.6 feet	1.4 to 2 feet
Neuman	500		0.05	2.5 to 6.5 feet	1.5 to 4 feet	1 to 2 feet

K – hydraulic conductivity, S – storage coefficient, S_y – specific yield
* - assumes all 258 lots are occupied by full-year residents, pumping 0.5 acre feet per year per well.

In general, any of these pumping scenarios results in mining of the water table, or using ground water faster than it can be recharged. However, the overall effect on a 100 to 200 foot saturated zone in the White Mountains aquifer would be minimal, whether it is the result of pumping from two wells, 258 wells, or even a single well.

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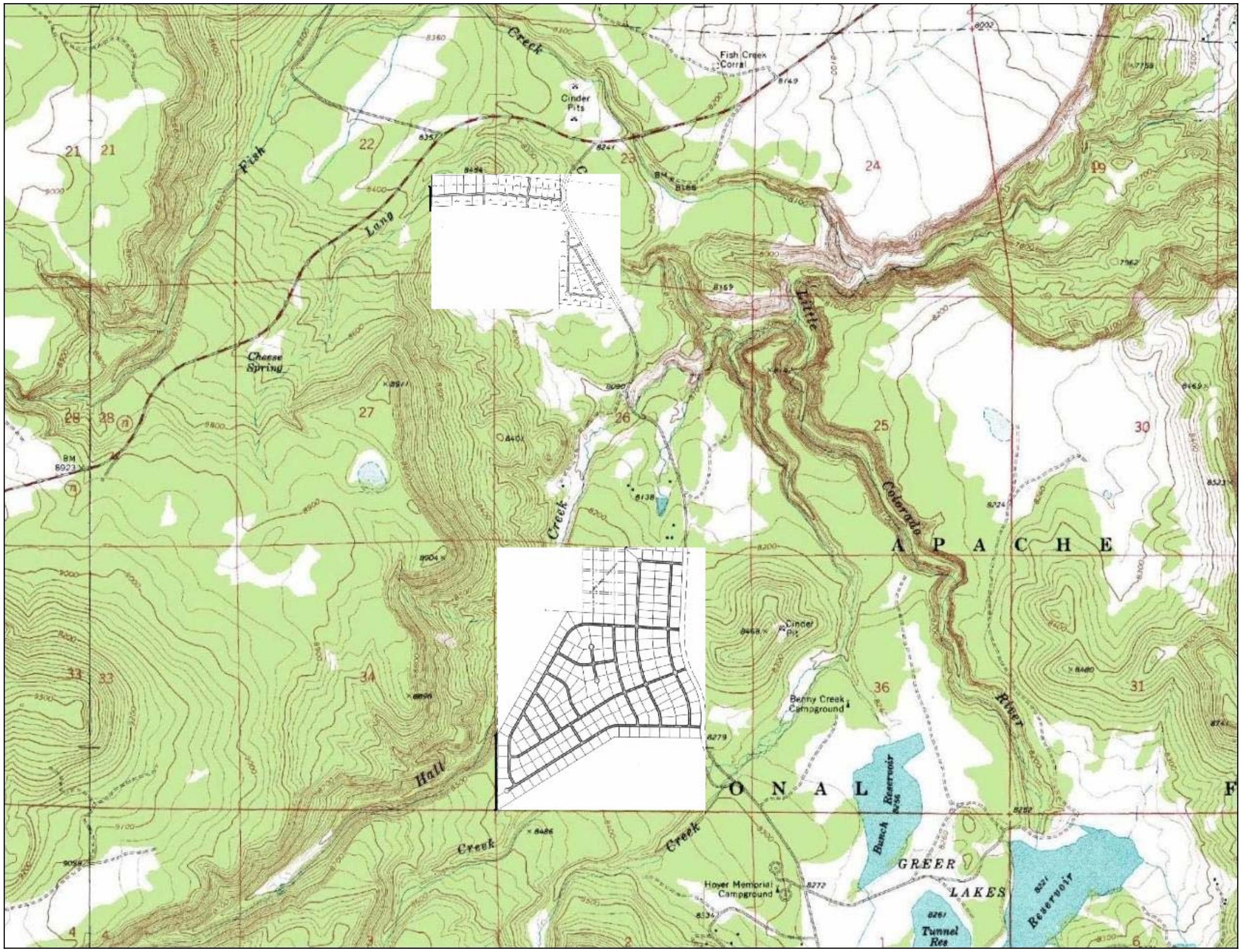

Figure 1. Location map for the two Black River exchange tracts, showing tract A and B locations. This image was utilized to locate hypothetical multiple wells in the analytical and MODFLOW simulations.

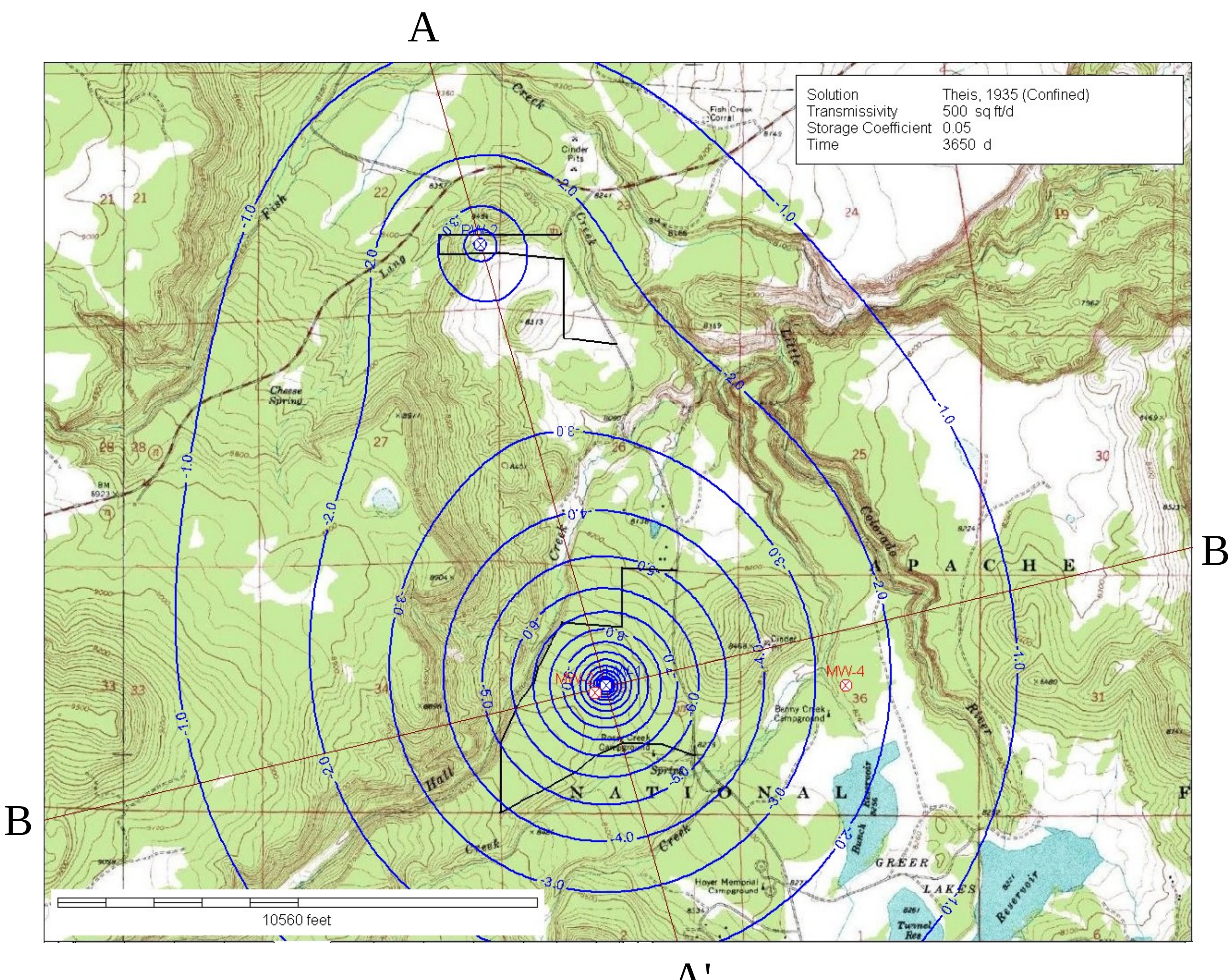

Figure 2. The ten year cone of depression for the two well pumping scenario. Drawdown contours resulting from 80 gpm pumping are in feet of decline from the initial water level. Aquifer parameters are shown on the map. Scale bar for all figures is 2 miles. The Theis solution was used with a transmissivity of 500 ft^2/d. Red lines denote the locations for the north-south and east-west cross sections shown below, and are only labeled in this figure.

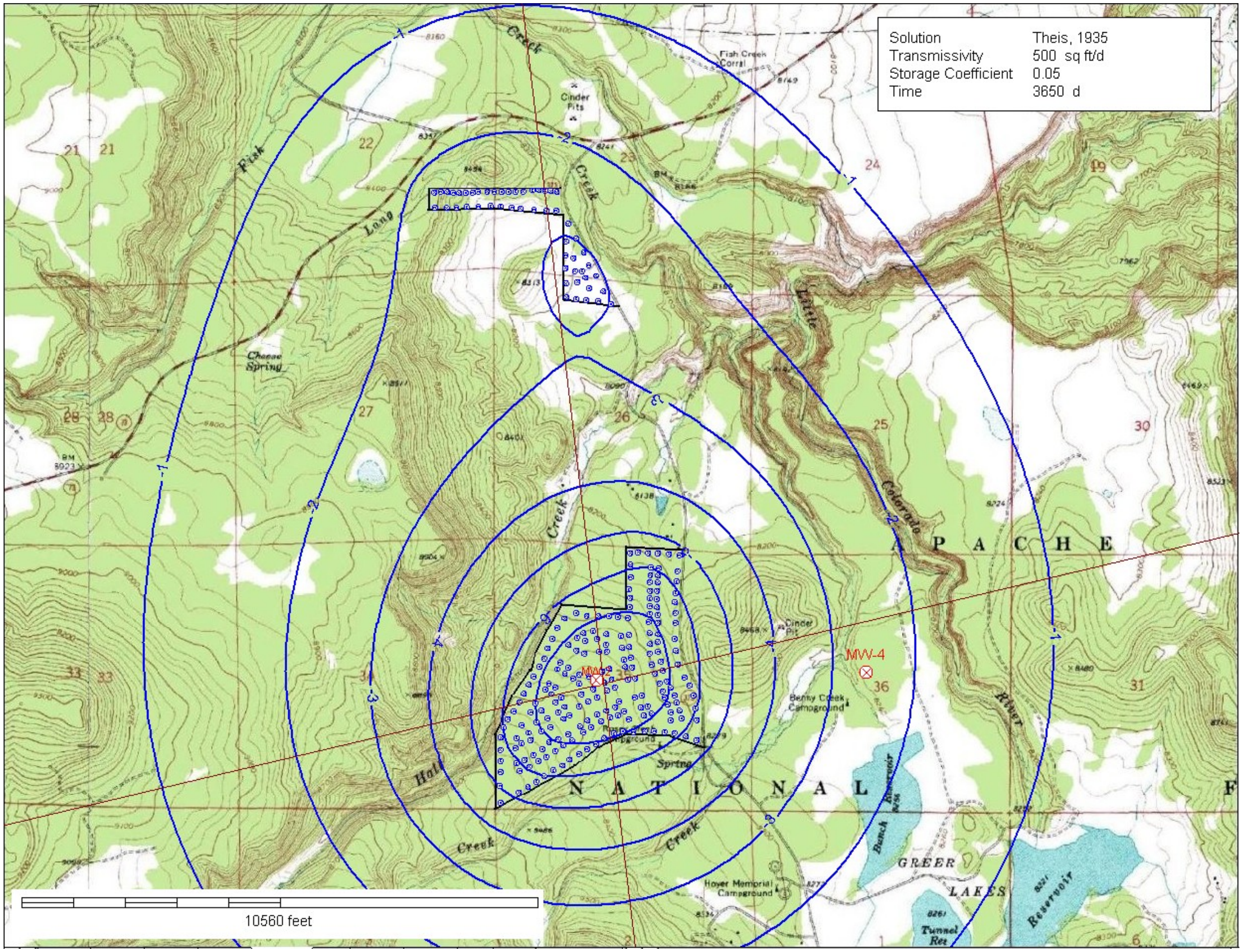

Figure 3. The ten year cone of depression for the 258 well pumping scenario. Drawdown contours resulting from 80 gpm pumping are in feet of decline from the initial water level. Pumping wells are the small blue symbols within each of the two development tracts. The Theis solution was used with a transmissivity of 500 ft^2/d.

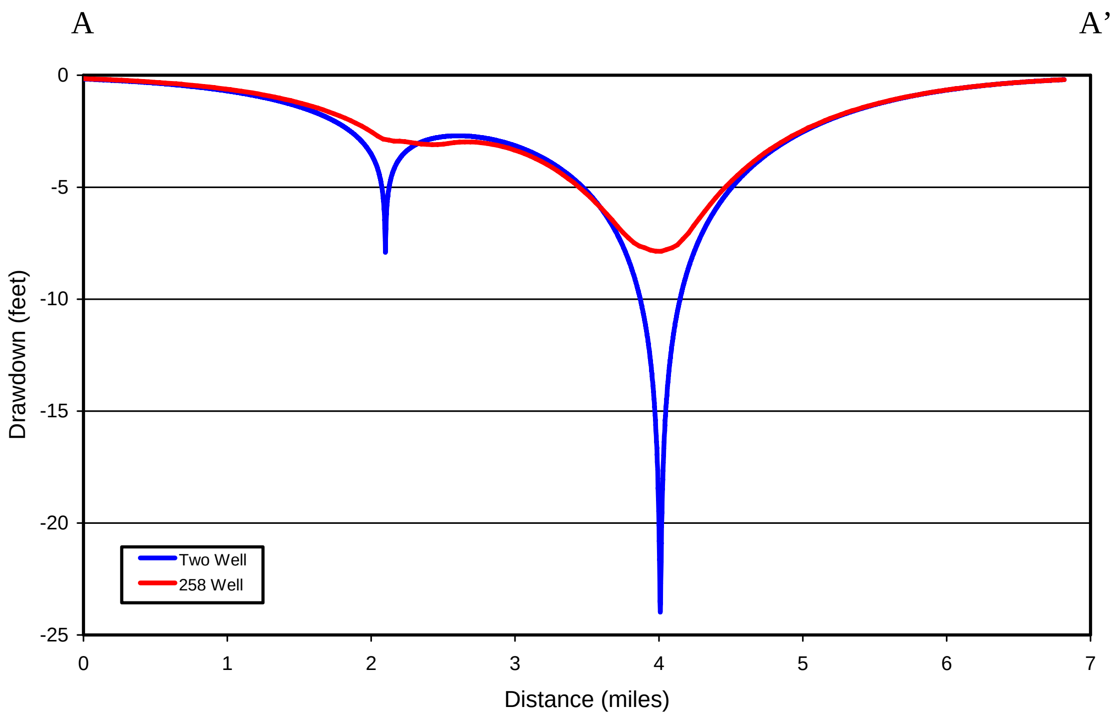

Figure 4. North-south (A-A’) cross section of the pumping scenario in Figures 2 and 3. The lines are the decline in the water table after 10 years of pumping. Pump rate is 80 gpm.

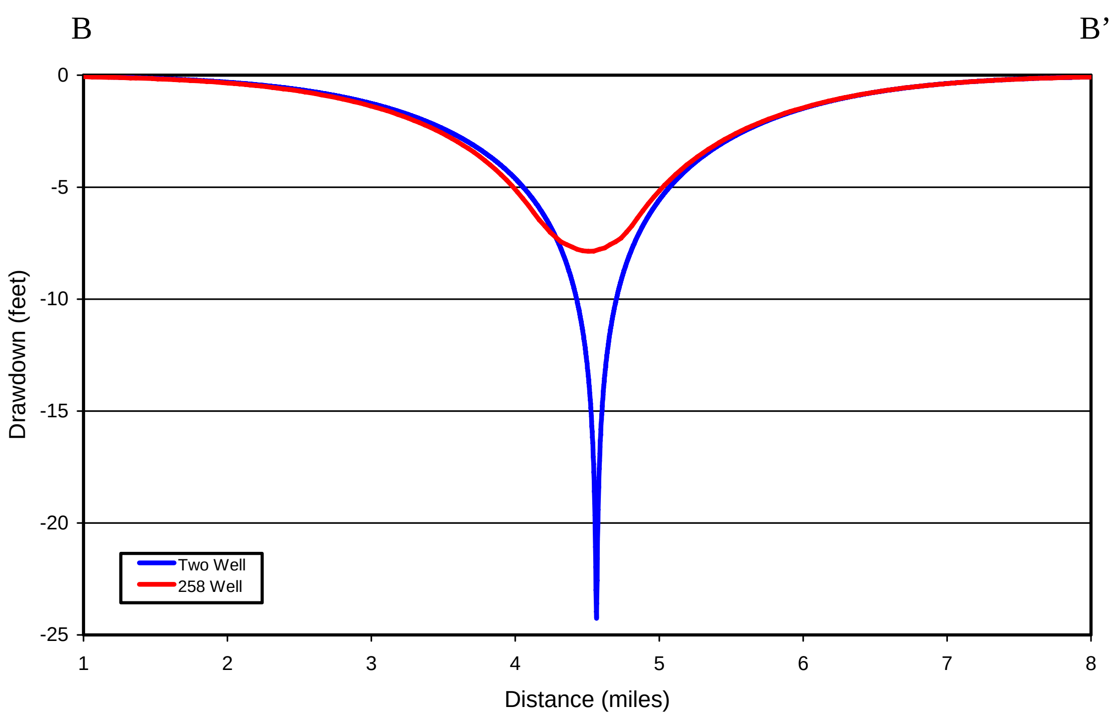

Figure 5. East-west (B-B’) cross section of the pumping scenario in Figures 2 and 3. The lines are the decline in the water table after 10 years of pumping. Pump rate is 80 gpm.

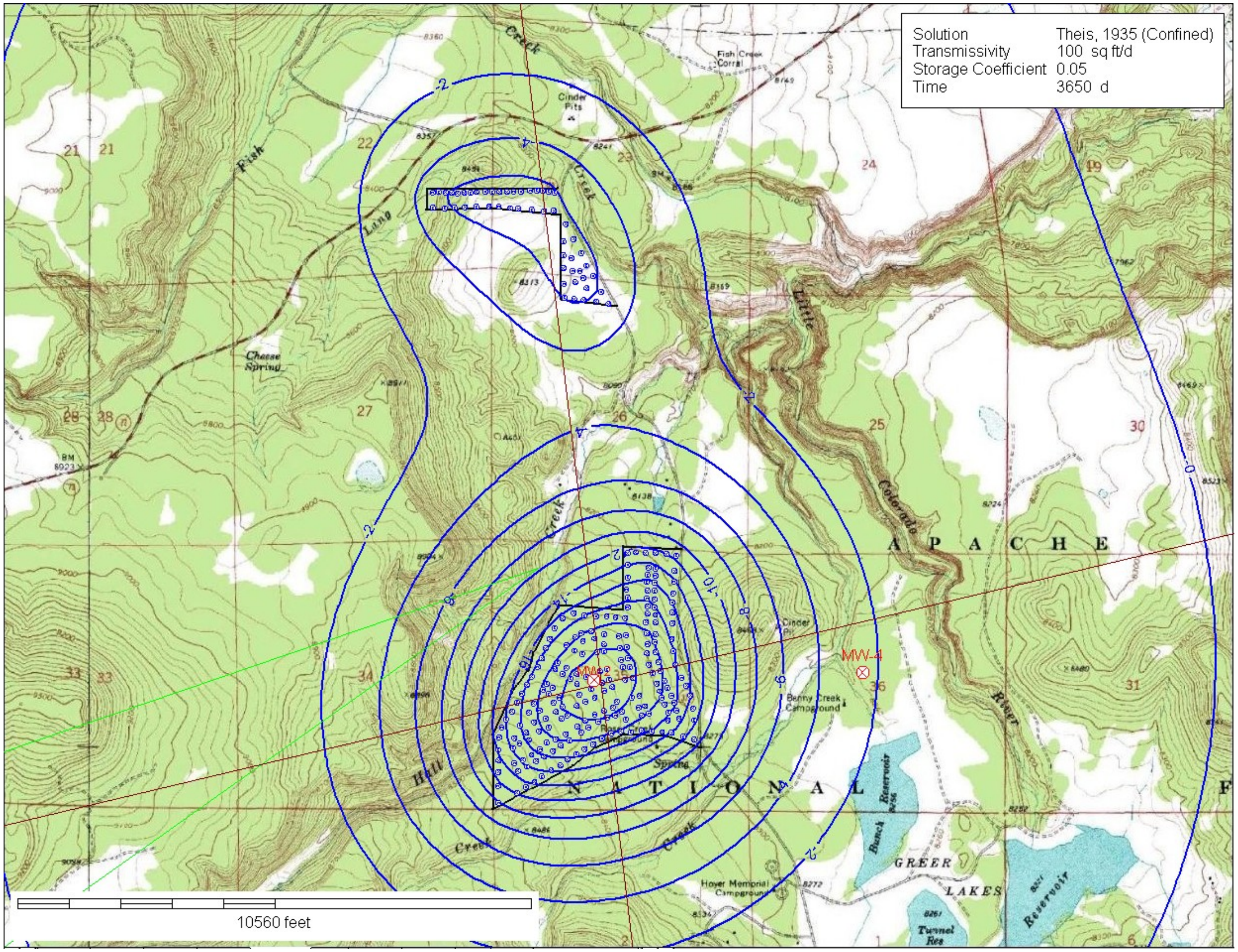

Figure 6. The Theis solution at a transmissivity of 100 ft^2/d after ten years of pumping 80 gpm. All other parameters are the same. Time is 10 years.

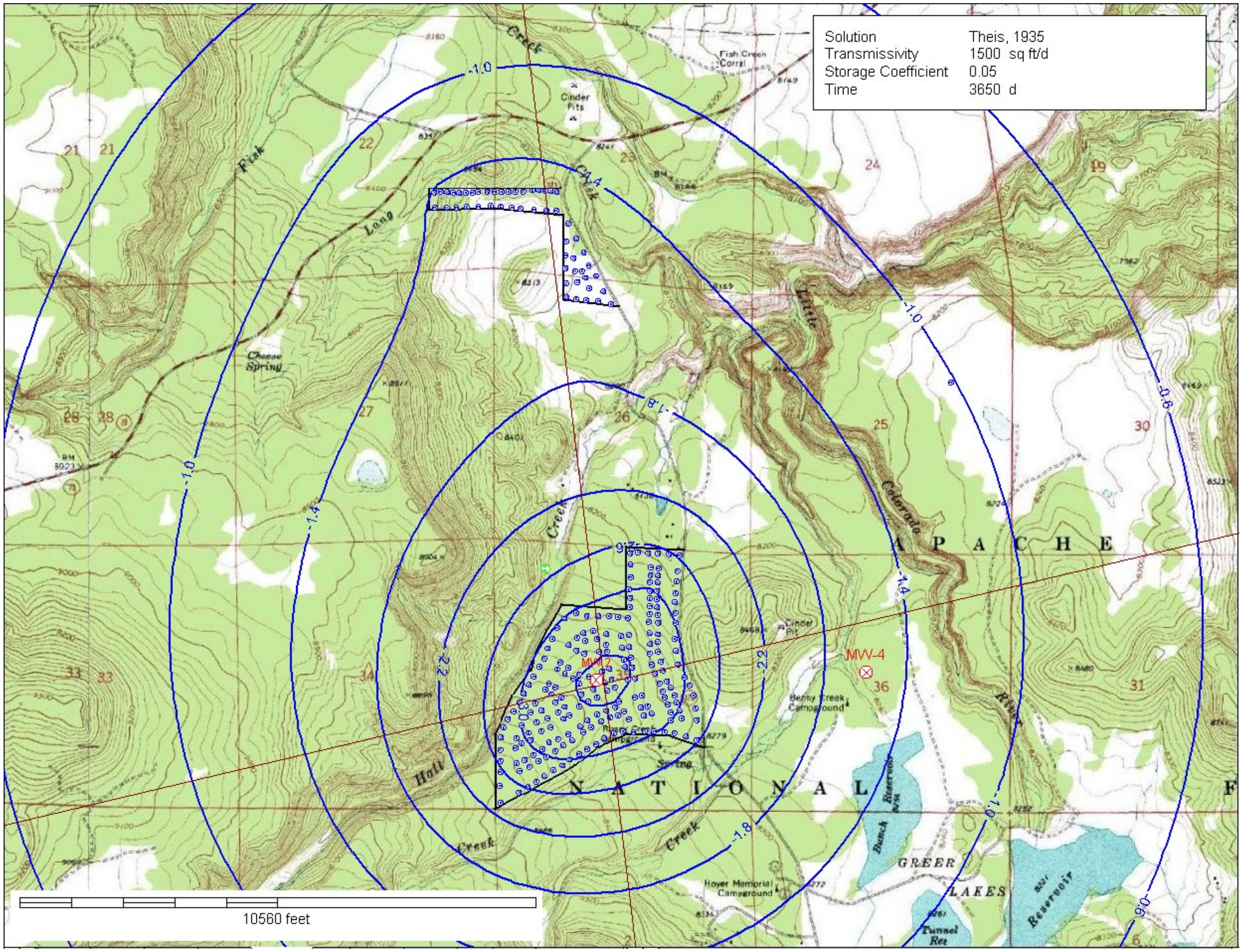

Figure 7. The Theis solution for drawdown with a transmissivity of 1500 ft2/d after ten years of pumping 80 gpm. All other parameters are the same. Time is 10 years.

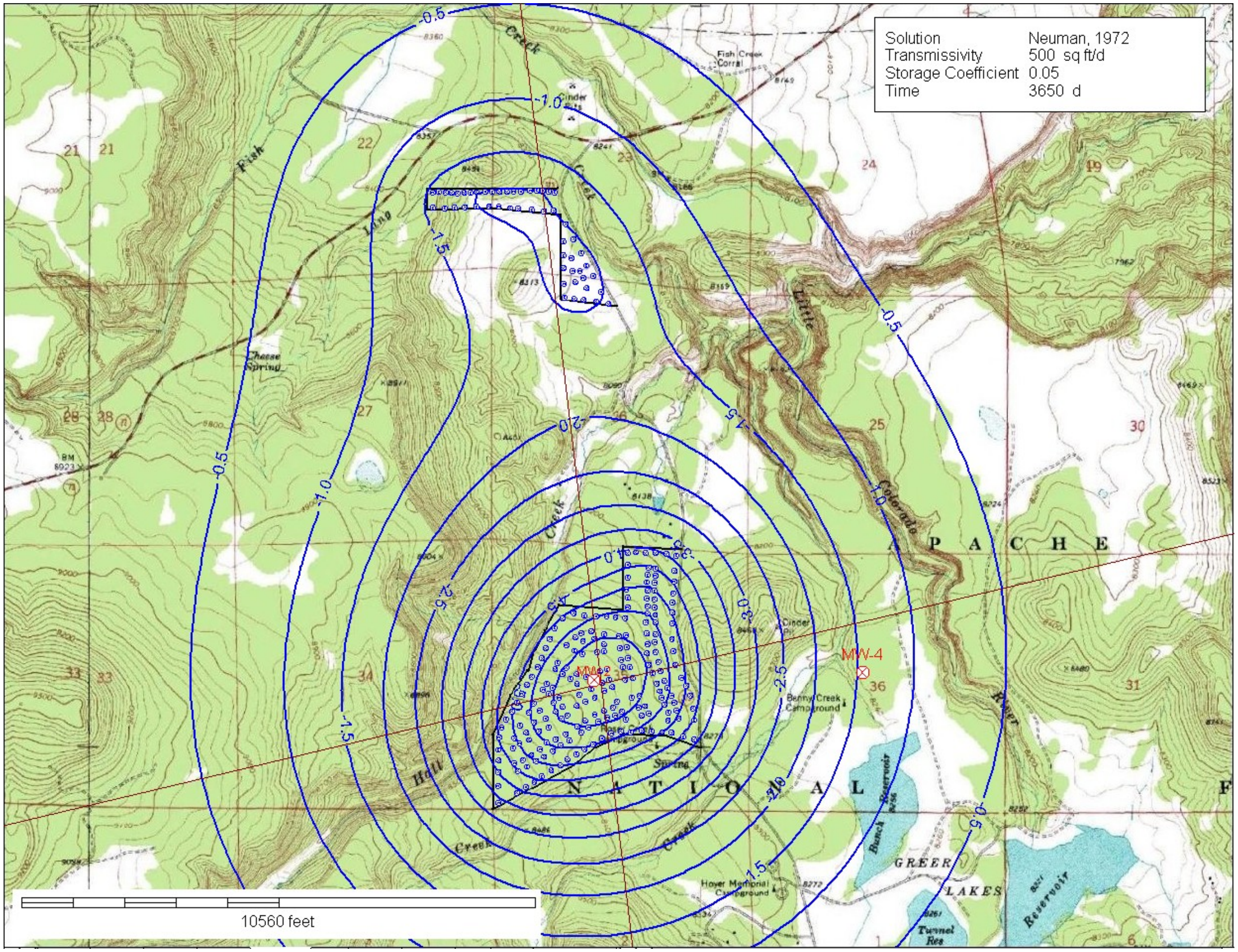

Figure 8. The Neuman solution for drawdown with a transmissivity of 500 ft^2/d after 10 years of pumping 80 gpm. All other parameters are the same. Time is 10 years.

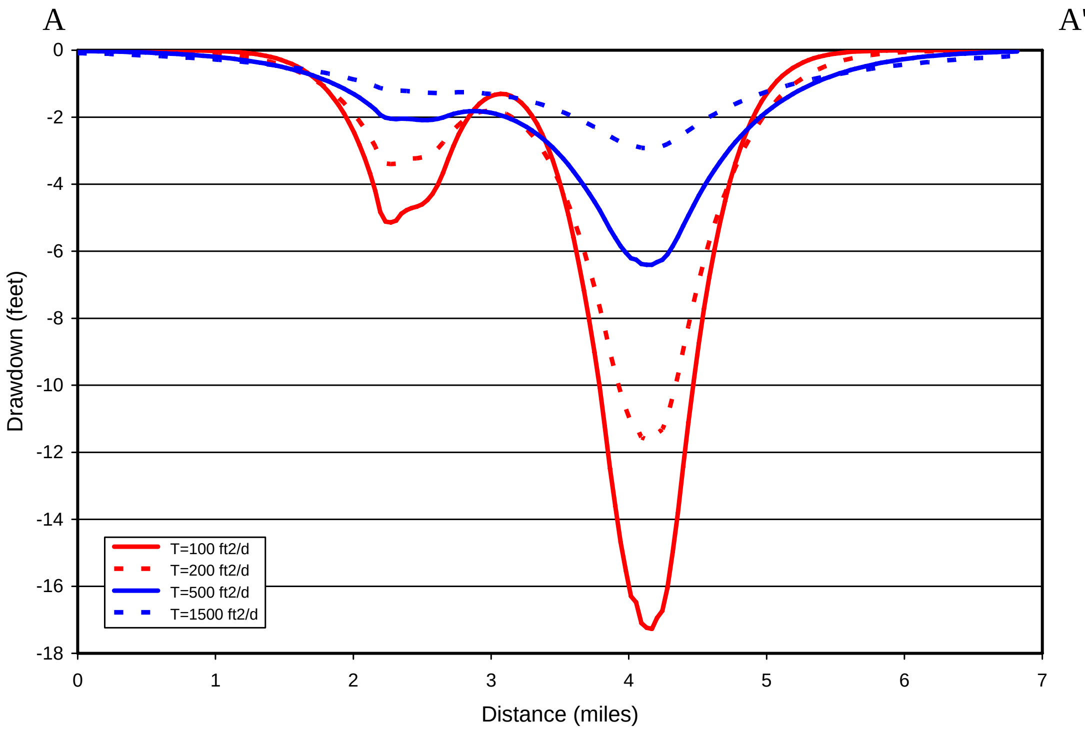

Figure 9. North-south cross section of the Neuman solution for transmissivities of 100, 200, 500, and 1500 ft^2/d

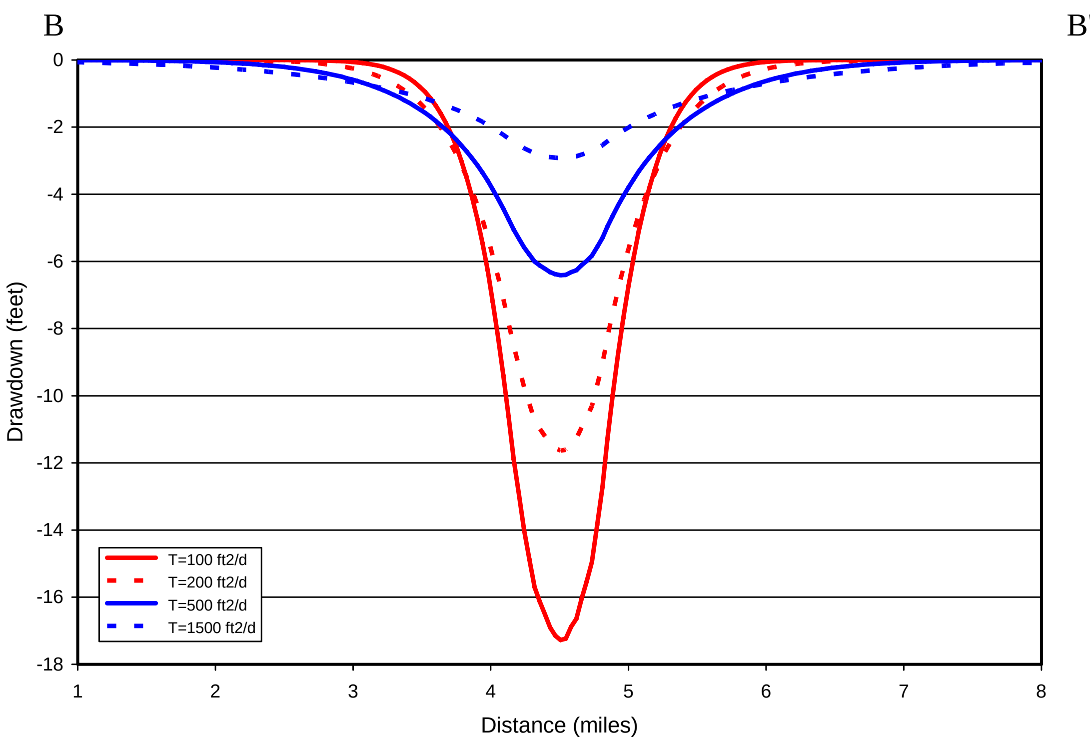

Figure 10. East-west cross section of the Neuman solution for transmissivities of 100, 200, 500, and 1500 ft^2/d

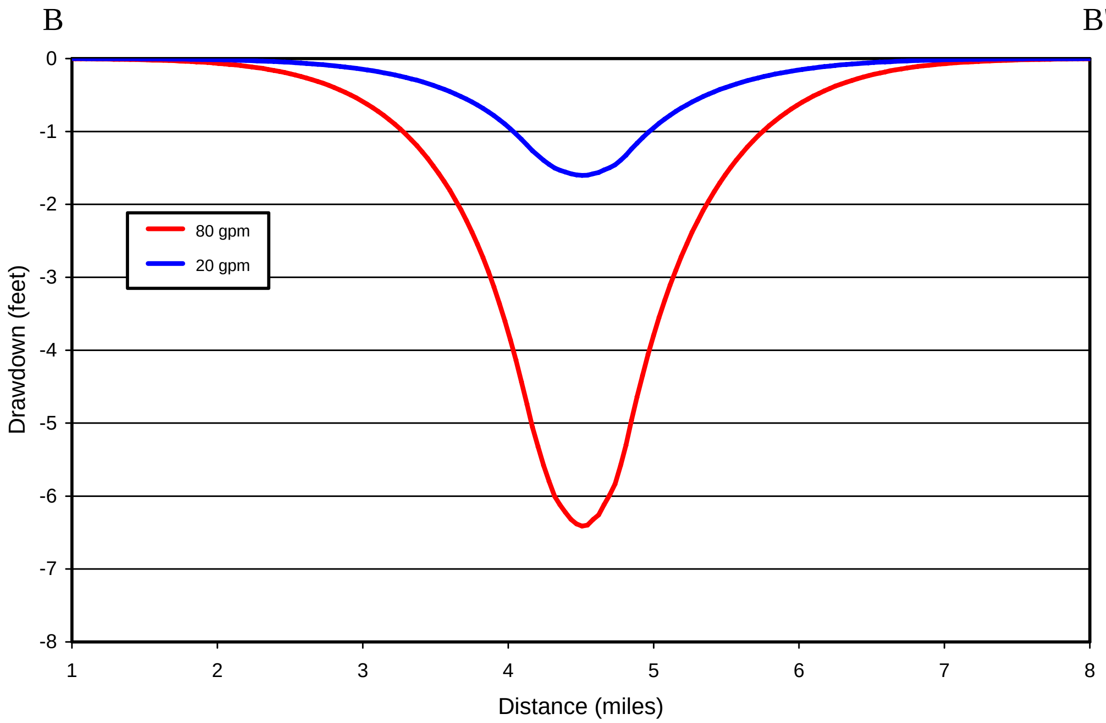

Figure 11. The East-west cross section for the Neuman solution at 80 and 20 gpm. Drawdown is directly proportional to pumping rate for this and all other scenarios. Transmissivity is 500 ft^2/d. A lower pumping rate cone of 20 gpm is also shown, in the event of part year residents (three months/year).

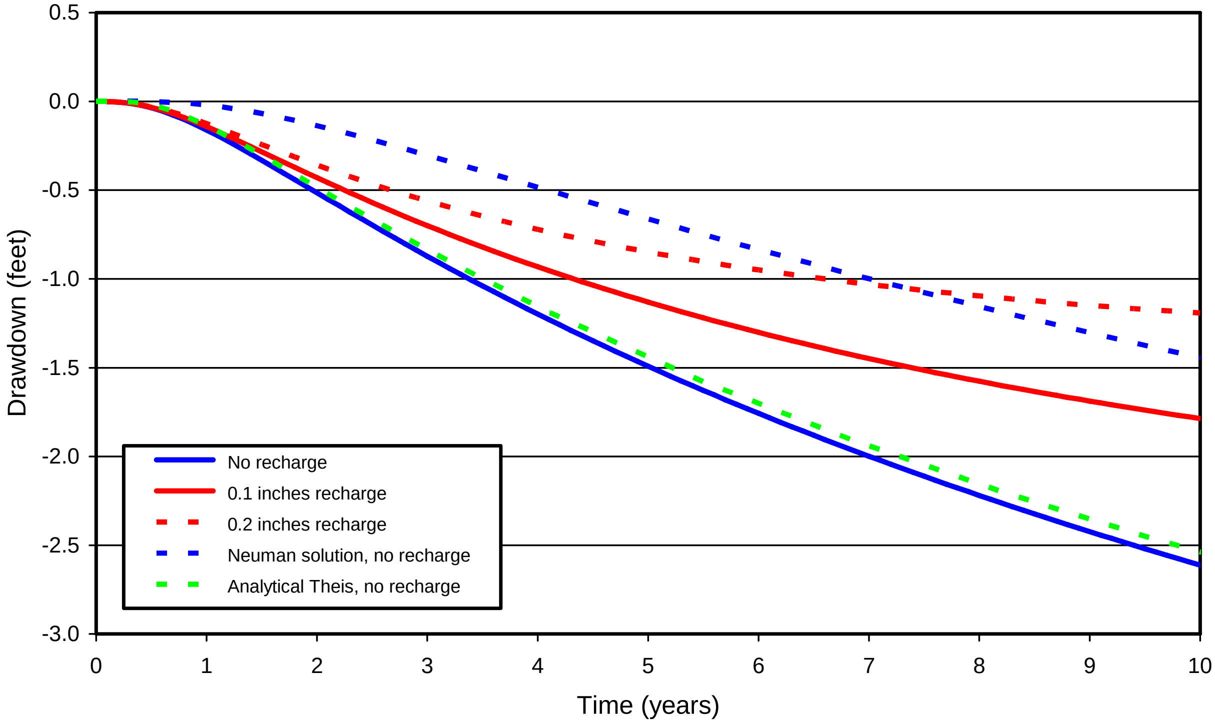

Figure 12. Time-drawdown graph for a point one mile east of the pumping wells. This shows the close similarity of the MODFLOW simulation to the Theis solution. Also note the effect of the addition of recharge in the MODFLOW simulation. Transmissivity is 100 ft^2/d.

DEFINITIONS OF TERMS

AQUIFER A water-bearing layer of rock that will yield water in a usable quantity to a well or spring.
CONE OF DEPRESSION: The depression of heads around a pumping well caused by the withdrawal of water.
CONFINING BED: A layer of rock having very low hydraulic conductivity that hampers the movement of water into and out of an aquifer.
DRAWDOWN :The reduction in head at a point caused by the withdrawal of water from an aquifer.
EQUIPOTENTIAL LINE: A line on a map or cross section along which total heads are the same.
GROUND WATER: Water in the saturated zone that is under a pressure equal to or greater than atmospheric pressure.
HYDRAULIC CONDUCTIVITY: The capacity of a rock to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.
HYDRAULIC GRADIENT: Change in head per unit of distance measured in the direction of the steepest change.
POROSITY: The voids or openings in a rock. Porosity may be expressed quantitatively as the ratio of the volume or
openings in a rock to the total volume of the rock.
POTENTIOMETRIC SURFACE: A surface that represents the total head in an aquifer; that is, it represents the height above a datum plane at which the water level stands in tightly cased wells that penetrate the aquifer minerals.
SATURATED ZONE: The subsurface zone in which all openings are full of water.
SPECIFIC YIELD: The ratio of the volume of water that will drain under the influence of gravity to the volume of saturated rock.
STORAGE COEFFICIENT: The volume of water released from storage in a unit prism of an aquifer when the read is lowered a unit distance.
TOTAL HEAD: The height above a datum plane of a column of water. In a ground-water system, it is composed of elevation head and pressure head.
TRANSMISSIVITY: The rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It equals the hydraulic conductivity multiplied by the aquifer thickness.
UNSATURATED ZONE: The subsurface zone, usually starting at the land surface, that contains both water and air.
WATER TABLE: The level in the saturated zone at which the pressure is equal to the atmospheric pressure.